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A microsimulation based method to evaluate shared space performances

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A microsimulation based method to evaluate shared space performances

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Kurzfassung

Shared Space ist ein Konzept der urbanen Straßengestaltung, das die Schaffung von niveaugleichen Zonen im gesamten Straßenquerschnitt beinhaltet, und darauf abzielt, die verschiedenen Verkehrsteilnehmer zu ermutigen, spontan zu interagieren und den Vorrang untereinander auszuhandeln. Um erfolgreiche Shared Spaces zu gestalten, können sich Ingenieure derzeit auf spezifische Richtlinien, sowie auf technische Berichte stützen. Dennoch gibt es keine Methode, um die Qualität des Shared Space im Hinblick auf den Level of Service (LOS) zu kalkulieren.

Daher wird ein neuer Verkehrsqualitätsindikator für Fußgänger entwickelt. Diese Erfolgsmessgröße berücksichtigt Komfortaspekte hinsichtlich der von Fußgängern zur Querung der Straßen benutzten Übergänge. Während der Überquerung wird durch das Aushandeln des Vorrangs mit den Fahrzeugen ein Unbehagen erzeugt. Daher werden potentiell komfortbeeinflussende Faktoren mathematisch formuliert. Später kann der Leistungsindikator auf Basis der Ansicht einer Umfragegruppe, die reale Straßenüberquerungen in Videosequenzen auswertet, kalibriert werden. Die Effektivität und Tauglichkeit des entwickelten Indikators wird in einer exemplarischen Fallstudie im Hamburger Bezirk Bergedorf demonstriert. Hierzu wird der dortige Shared Space gefilmt. Um die Interaktion von Verkehrsteilnehmern und die Wirkungsweise der Verkehrsraumaushandlung nachzustellen, wird ein innovativer Modellierungsansatz, der auf dem sozialen Kräftemodell basiert, empfohlen. Das Modell wird in einem Java-basierten Simulationstool kalibriert und implementiert. Verschiedene Shared Space Arten und konventionelle Szenarien mit Raumtrennung werden simuliert.

Das Ziel dieser Dissertation ist es, ein Verfahren zur Auswertung der Performances von Shared Spaces durch Verkehrsmikrosimulation zu entwickeln. Dieses Verfahren beinhaltet die Datenerhebung und –erfassung, die Definition der Leistungsindikatoren, die Entwicklung eines Mikrosimulationsansatzes und die Kalibrierung des Bewegungsmodells auf Basis realer Daten. Zudem werden Simulationen durchgeführt, um Ergebnisse zu sammeln. Des Weiteren zeigt diese Arbeit die Notwendigkeit, einen komfortbasierten Indikator für die Verkehrsqualität der Fußgänger in Shared Spaces zu verwenden. Die Vorteile dieses Ansatzes, gegenüber konventionellen, effizienzbasierten Indikatoren wie z.B. Zeitverzögerungen, werden entsprechend in praxistauglichen Situationen dargestellt und sukzessiv mittels statistischer Verfahren veranschaulicht.

Abstract

Shared space is a concept of urban street design which implies the creation of a level surface within the whole road reserve and is aimed at encouraging different road users to interact spontaneously and to negotiate priority with each other. To build successful shared spaces, traffic engineers can rely at present on specific guidelines as well as technical reports. Nevertheless, there is no method available to compute the performance of shared spaces in terms of Level Of Service (LOS).

In order to address this gap, a new indicator of traffic quality for pedestrians is being developed. This measure of performance considers aspects of comfort related to the crossing, which pedestrians use to go from one side of the roadway to the other. During this movement, discomfort is generated by the necessity to solve the conflicts with vehicles. Therefore, factors which potentially influence comfort are mathematically formulated. Later, the performance indicator can be calibrated on the basis of the opinion of a group of respondents, who evaluated real-world crossing movements in video sequences. The effectiveness and usability of the developed indicator is demonstrated in an exemplary case study. A shared street in the district of Bergedorf, Hamburg (D) is selected and filmed. To reproduce the interaction of road users and the mechanism of space negotiation, an innovative modeling approach based on social force model (SFM) is proposed. The model is calibrated and implemented in a Java-based simulation tool. Alternative shared space scenarios, as well as conventional ones with space segregation, are simulated.

The goal of this dissertation is to establish a method to evaluate the performances of shared spaces through traffic microsimulation. This method includes the data survey and acquisition, the definition of performance indicators, the development of a microsimulation approach, the calibration of the motion model on the basis of real-world data and finally the execution of simulations to collect the results. In addition, this work shows the necessity to employ a comfort-based indicator for pedestrian traffic quality in shared spaces. The benefits of this approach, with respect to conventional efficiency-based indicators as time delay, is properly shown in real-world situations and successively demonstrated by help of statistical methods.

For whom I love,

Laura Magnabosco

Claudio Pascucci

Giulia Pascucci

Stefania Mosconi

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Declaration

I hereby declare that this work has not been submitted for any other degree at this University or at any other institution and that, except where reference is made to the work of other authors, the material presented is original. Some portions of the thesis chapters have been published as follows:

- parts of Chapter 3 in [58];
- parts of Chapter 4 in [58, 60];
- parts of Chapter 5 in [59, 67, 70, 71];
- parts of Chapter 6 in [70, 60];
- parts of Chapter 7 in [61].

Moreover, the modeling framework described in Chapter 5, as well as part of the calibration issue discussed in Chapter 6, was developed within the research project MODIS (Multi mODal Intersection Simulation) in the period March 2014 - August 2017. MODIS was granted by the *Deutsche Forschungsgemeinschaft* (DFG) under the references BE 2159/13-1 / FR 1670/13-1 and involved the Institute for Transportation and Urban Engineering at the *Technische Universität Braunschweig* (D) and the Institute for Risk and Reliability at the *Leibniz Universität Hannover* (D). The cooperation has resulted in four scientific publications [59, 67, 70, 71], which are properly mentioned in the course of this dissertation.

Braunschweig, April 2020

Federico Pascucci

Preface

I had my first real experience with “space negotiation” at 18 years old whilst on a family trip to Rome. Before reaching the Grande Raccordo Anulare - the well-known ring road surrounding the capital city - my father glanced at me through the rear-view mirror and asked me, “Federico, would you like to drive to grandma’s house?”.

Of course, I accepted the offer in the blink of an eye. The opportunity to test myself in the dreadful Roman traffic, with only a few days since getting my license, had all the makings of a great challenge to beat.

Well, it did not go very well. After the initial phase of euphoria, which lasted just enough time for a few intersections, I began to feel insecure, inadequate, and unprepared. Indeed, things were not exactly the way I had learned them at driving school.

First of all, the streetscape was less self-explaining than the ones I had first trained in during driving lessons in Padua. In numerous instances I struggled to understand which behaviour the road was expecting of me, but the biggest problem was my fellow “road companions.” Scooters were overtaking me on both sides and bustling around me like a swarm of bees. At the intersections, motorists positioned themselves in a chaotic manner, slipping in any open gap they could find. When travelling on the main road with the right of way, it was very likely to encounter a cheeky driver attempting to slide in from secondary roads, thereby forcing me to either accelerate aggressively to reinforce my right of way, or brake harshly and give in to their demand. Alternatively, I could honk, this third option being the one my father recommended but that I personally did not see the point in.

For a young driver such as myself, who until a few days prior had been studying for the theoretical part of the exam, this type of barely “spontaneous” interaction between drivers was difficult to fathom. It was as if I had somehow missed some comments in the Highway Code, footnotes at the bottom of the page which expressed: “Right of way? True, but with some flexibility.” Or: “Lanes? Of course, but do slip in if there is a gap.” “Motorcycles can also overtake you from the right, personal preference overrides all.”

It was hardly pleasant to suddenly find myself engulfed in this confusion. To use a word that is mentioned frequently throughout this thesis, it can be stated that I did not find myself in my *comfort* zone.

Nonetheless, there is a silver lining to the tale: a few years later I would deal with shared space and having had this experience first-hand would prove to be very useful. Ultimately, one cannot speak of “space negotiation” without having had the chance to drive around Rome at least once. Allow me to clarify.

This thesis discusses the principle by which, when horizontal and vertical road markings are reduced, road users react to this “deregulation” by raising their attention threshold towards others. In shared space, this is the desired and researched effect: pedestrian crossings and “give way” signs are removed, and through other ploys such as the implementation of paved and coloured surfaces replacing grey tarmac, individuals are coaxed into increased responsibility and increased awareness towards one another. This means that, in the absence of the various common indicators on the behaviour to observe, road users will need to look at each other more intently so as not to collide.

In Rome, this “deregulation” is perceived more. Zebra crossings are not always clearly marked, often they are faded or ruined with the passing of time. Street signs are occasionally worn. The road environment is partially neglected and is not, in fact, “self-explaining”: it does not clearly indicate the behaviour it wants us to follow. In light of this absence, there is more room for interpretation, something which does not occur on a Swiss road. For example, at the branches of intersections we can position ourselves according to the logic of good sense, seeing as how the lanes are not clearly delineated.

What is the consequence? In Rome, communication between motorists is very much enforced by glares, honks, and high beams. Through these measures, drivers communicate various intentions: “Careful, I’ll go first,” “ Yes, I saw you,” “Wake up, the light is green.” When my father told me to honk, he probably meant that I had to communicate one of these statements, but I was not fluent in this language. It was Chinese: I could not understand it nor could I grasp a single word.

Nonetheless, for those who are used to it, this way of communicating is something they are not willing to give up, even if a clear, well-delineated, and regulated road were offered in return. Indeed, it is a well-known fact that those who frequently practice this form of communication at the wheel do not enjoy cruising in German-speaking countries: they are constantly scared to do something wrong or make a mistake. They feel oppressed.

This is indeed one of the major topics discussed throughout the course of this thesis: is there some sort of beauty, satisfaction, and charm in being able to negotiate space when there is the freedom to do so, instead of comfortably complying to the rules of a clear and regulated streetscape? Are there reasons to prefer the first option?

In order to answer this question, over the years, I have often referred back to a situation that we all experience on a daily basis: that of crossing a busy street as pedestrians. In the first scenario there is an unquestionable and unrelenting traffic light. Thus, as usual, one waits for the green light before crossing. In the second scenario nothing is there and so it is necessary to negotiate space: a pedestrian waits for a sufficient time gap to appear between the moving cars, he signals his intention to cross, waits for the driver to slow down and perhaps show their acknowledgment via headlights, and finally the pedestrian waves a sign of thank-you and crosses.

Which scenario is better? If you ask a Roman, he will most likely throw the traffic light at your head.

For what reason then is the latter scenario in some ways more appealing than the former for some people? I propose two plausible explanations as I attempt to put myself in the shoes of those who, unlike myself, reject the simplicity and charm of traffic lights.

The first explanation is that using the “space negotiation” method to cross the road makes us feel free to make a choice, our choice, without waiting for an electronic device to make it on our behalf. I can cross the road where I want, in the direction I want, and between the gap of cars that I like the most. This is an extreme kind of freedom.

The second explanation has to do with our sociability: in other words, when an interaction among strangers is successful, this can lead to a sort of fulfilment for the individuals involved. Think about when a group of party goers, perhaps celebrating a graduation or a bachelorette, stops us outside to ask for a photo together. What do we do? Most likely, we walk away with a smile and maybe tell someone at home. See, receiving “familiar” behaviour by “non-familiar” people conveys positivity to the world around us. Accordingly, flashes of headlights from a passing driver to motion us to cross the road is a positive feedback from someone who does not know us and can thereby induce a sense of contentment.

So, let’s face it: negotiating space and interacting holds a certain charm.

However, as a traffic engineer, I felt the need to place some restrictions on the overly simplified concept of “negotiating is good.” This is where the idea for this thesis was born. Negotiating is not always good. For example, if the road is full of vehicles, negotiating becomes somewhat of a nightmare. If the car in front of us does not slow down, the potential positive feedback can turn into a collision with drastic consequences.

To put it as engineers do, negotiating is alright as long as the two cardinal conditions of engineering are not lacking: first, it must work; and second, it must be safe. To these I add a third additional condition: the interaction is good if it provides *comfort*.

Such is my main discovery in this thesis: in the areas in which space negotiation is practiced, traffic quality must be measured by also keeping in mind *comfort*. When all is said and done, I reached grandma's house on time on that God forsaken day in Rome, without risking any car crash. But it was my lack of *comfort* in the end that prompted me to say, "Dad, next time I'm taking the train!".

I wish you a good reading!

Prefazione

La mia prima forte esperienza di “negoziazione degli spazi” l’ho avuto all’età di 18 anni mentre ero in viaggio con la mia famiglia verso Roma. Prima di giungere al Grande Raccordo Anulare – la famosa tangenziale che circonda la Capitale – mio padre mi fissò tramite lo specchietto retrovisore e mi chiese: “Federico, vuoi guidare tu fino a casa della nonna?”

Io, ovviamente, accettai senza battere ciglio. L’occasione di mettermi alla prova nel temibile traffico romano, con la patente conquistata solo da qualche giorno, aveva tutti gli ingredienti per essere una bella sfida da vincere.

Ecco, non è andata benissimo. Dopo una breve fase di euforia, durata giusto il tempo di qualche incrocio, ho iniziato a sentirmi insicuro, inadatto, impreparato. Le cose infatti non erano esattamente come le avevo imparate a scuola guida.

Prima di tutto l’ambiente stradale era meno “auto-esplicativo ” di quelli in cui avevo fatto le prime prove di guida, a Padova. In molte situazioni faticavo a comprendere quale comportamento la strada si aspettasse da me. Ma il problema maggiore erano i miei “compagni della strada”. C’erano motorini che sorpassavano da entrambi i lati e che mi ronzavano attorno come uno sciame d’api. Alle intersezioni gli automobilisti si disponevano in maniera caotica, infilandosi in ogni spazio libero. Viaggiando sulla strada principale, con diritto di precedenza, era molto probabile incontrare qualche buontempone che provava ad inserirsi dalle strade secondarie, costringendomi ad accelerare in maniera aggressiva per ribadire il mio diritto di precedenza oppure a frenare bruscamente per dargliela vinta. O a suonare il clacson (questa terza opzione era quella che mi suggeriva papà, ma io non ne comprendevo il fine).

Per un neopatentato come me, che fino a qualche giorno prima studiava la teoria per l’esame, questo tipo di interazione tra automobilisti a dir poco “spontanea” era molto difficile da concepire. Era come se nel Codice della Strada mi fossero sfuggite delle postille, delle note a piè di pagina in cui si specificava: “Precedenza? Vero. Però si richiede un po’ di flessibilità”. Oppure: “Corsie? Certo, ma se c´è spazio infilatevi pure”, “I motorini possono sorpassare anche a destra, vige la regola del gusto personale”.

E trovarsi all'improvviso immersi in questa confusione non è stato piacevole. Utilizzando una parola molto in voga in questa tesi, possiamo affermare che non mi trovavo in una situazione di *comfort*.

Ma c'è il consueto lato positivo della storia: qualche anno dopo mi sarei occupato di *shared space*, e aver vissuto in prima persona questa esperienza si sarebbe rivelato molto utile. In fondo, non puoi parlare di "negoziazione degli spazi" se non ti sei fatto almeno una volta nella vita un giretto in macchina a Roma. Mi spiego meglio.

In questa tesi viene esposto il principio per cui, quando la segnaletica orizzontale e verticale si riduce, gli utenti della strada reagiscono a questa "deregolamentazione" alzando la loro soglia di attenzione verso gli altri utenti. Negli *shared space* questo effetto è voluto, è ricercato: si fanno sparire le strisce pedonali e i segnali di "dare precedenza" e tramite altri escamotage - come ad esempio l'impiego di una superficie pavimentata e colorata al posto del grigio asfalto – si spingono gli utenti verso una maggiore responsabilizzazione, una maggiore consapevolezza l'uno dell'altro. Vuol dire che, mancando le numerose comuni indicazioni sul comportamento da osservare, gli utenti della strada avranno bisogno di cercarsi di più con lo sguardo, così da non urtarsi a vicenda.

A Roma si può effettivamente percepire una sorta di "deregolamentazione". Le strisce non sono sempre tracciate, molte volte sono scolorite e rovinate dal passare del tempo. I cartelli stradali sono talvolta usurati. L'ambiente stradale è in parte trascurato. Non è, appunto, "auto-esplicativo": non indica chiaramente il comportamento che ci si aspetta da chi la utilizza. E alla luce di queste mancanze, c´è più spazio per la libera interpretazione – cosa che non c´è in una strada svizzera. Per esempio, ai rami delle intersezioni possiamo disporci secondo la logica del buon senso, dato che le corsie non sono esplicitamente indicate.

La conseguenza? A Roma tra gli automobilisti c'è una comunicazione molto spinta. Con lo sguardo, con il clacson, con gli abbaglianti. E attraverso questi strumenti gli automobilisti si comunicano le cose più svariate: "Attento, passo io", "Sì, ti ho visto", "Svegliati, è verde". Quando papà diceva di usare il clacson, intendeva probabilmente che dovevo comunicare una di queste cose. Ma io quella lingua non la sapevo parlare. Era arabo: non comprendevo né spiccicavo una parola.

Tuttavia, per chi ci è abituato, questa forma di comunicazione è qualcosa a cui non sarebbe disposto a rinunciare, anche se in cambio gli offrissero una strada chiara, ben delineata, ben regolamentata. È risaputo infatti che, per chi pratica regolarmente questa comunicazione al volante, spingersi nei paesi germanofoni non è sempre piacevole: alla guida si ha costantemente paura di sbagliare, di commettere un errore. Ci si sente oppressi.

Nello sviluppo di questa tesi uno dei maggiori temi di riflessione è stato appunto questo: c'è forse bellezza, piacere, fascino nel poter negoziare gli spazi - quando ci viene data la libertà per farlo - piuttosto che attenersi, comodamente, alle indicazioni di un ambiente stradale chiaro e regolamentato? Ci sono forse motivi per preferire la prima opzione?

Per rispondere a questa domanda, nel corso degli anni, ho fatto spesso riferimento a una situazione che viviamo tutti i giorni: quella dell'attraversamento di una strada trafficata come pedoni. Nella prima variante c´è un semaforo, inesorabile e ineluttabile. Quindi, come sempre, si aspetta il verde e poi si attraversa. Nella seconda variante invece non c´è un bel niente, quindi è necessario negoziare gli spazi: si aspetta che tra le auto in transito ci sia un *gap* temporale sufficiente, si accenna l'attraversamento, si aspetta che l'automobilista deceleri e magari "faccia i fari", quindi si ringrazia con la mano e si attraversa.

Quale vi piace di più? Perché se chiedete a un romano, il semaforo ve lo tira in testa.

Perché, quindi, il secondo scenario è per certi versi - e per certe persone – preferibile al primo? Vi propongo due motivi plausibili, cercando di mettermi nei panni di chi, a differenza mia, ripudia la semplicità e l'eleganza dei semafori.

Il primo è che attraversare con il metodo "negoziazione degli spazi" ci rende liberi di fare una scelta, la nostra scelta. Senza aspettare che un aggeggio elettronico ci dica cosa fare. Posso attraversare dove voglio, nella direzione che preferisco, scegliendo il "gap" tra le auto che più mi aggrada. Una forma di libertà estrema.

Il secondo ha a che fare con la nostra socialità: quando tra "sconosciuti" avviene un'interazione e questa va a buon fine, può generare tra i partecipanti una forma di appagamento. Pensiamo a quando per strada un gruppo di persone in festa – una festa di laurea, un addio al celibato – ci ferma e ci chiede, ad esempio, di fare una foto con loro. Che facciamo poi? Probabilmente ce ne andiamo con il sorriso e magari lo raccontiamo a qualcuno a casa. Ecco, ricevere un comportamento "familiare" da persone "non familiari" ci trasmette della positività verso il mondo circostante. In questo senso, ricevere i "fari" da un automobilista per esortarci a passare è un feedback positivo da qualcuno che non ci conosce, e può far piacere.

Quindi, mettiamocela via: negoziare gli spazi e interagire può avere qualcosa di affascinante.

Tuttavia, al concetto di "negoziare è bello" – riassunto in maniera banale – sentivo come ingegnere del traffico di dover porre dei paletti. Da qui l'idea di questa tesi.

Negoziare non è sempre bello. Ad esempio: se la strada è piena zeppa di auto, negoziare può diventare un incubo. Se l'auto davanti a noi non decelera, il potenziale feedback positivo può trasformarsi in un incidente con gravi conseguenze.

Per dirla proprio da ingegneri: negoziare va bene, ma a patto che non vengano a mancare le due condizioni cardine dell'ingegneria: primo che funzioni, secondo che sia sicuro. Più una terza condizione, che aggiungo io: che l'interazione è bella se è confortevole.

Che è peraltro la mia principale scoperta in questa tesi: nelle aree in cui si pratica la negoziazione degli spazi, la qualità del traffico va valutata anche tenendo conto del *comfort*. Perché io, quel benedetto giorno a Roma, a casa della nonna ci sono arrivato in tempo e senza rischiare incidenti. Ma è stata la mancanza di *comfort* che alla fine mi ha fatto dire: "Papà, la prossima volta io prendo il treno!"

Vi auguro buona lettura!

Contents

Nomenclature

General

LOS	Level Of Service	**SFM**	Social Force Model
MOE	Measure Of Effectiveness	**SSM**	Surrogate Safety Measures

Performance Indicators (Chap. 4 and 7)

IDR	Initial Deceleration Rate	**TE**	Traffic Environment
IV	Interaction with Vehicles	**VD**	Vehicle Delay
PC	Pedestrian Comfort	**VS**	Vehicle Speed
PET	Post Encroachment Time		

Modeling (Chap. 5 and 6)

AG	Aggressive reaction	**Ped**	Pedestrian
CU	Competitive User	**PR**	Prudent reaction
CUT	Competitive User's Trajectory	**TPC**	Time to Possible Collision
EU	Ego User	**Veh**	Vehicle
FFT	Free-Flow Trajectory	**XP**	Crossing Point
NR	No Reaction		

1 Introduction

While the logic of car-oriented street space has dominated in the development of cities for over half of the last century, in recent years environmental, public health, social, and economic reasons have pushed toward the re-think of urban design principles. Behind them there is the idea to move away from car hegemony and to make people - citizens - regain the urban space. In the words of Jahn Gehl, to reconfigure cityscapes into “places for people” [27].

In the field of transportation planning, this is reflected in two policies to be implemented as a complement. First, to reduce car traffic demand by making car driving “less attractive” while making sustainable transport modes “more attractive”. This includes on the one hand discouraging the use of private cars (less physical space for cars, lower speed limits) and on the other hand promoting the shift toward sustainable urban transport modes, as public transport and forms of sharing mobility. Second, to increase and improve the space for pedestrians. This includes placemaking, namely, the creation of vibrant public spaces, which should increase the desire to walk and, above all, the improvement of walkability by providing better walking facilities.

In order to fulfill these goals, public authorities can adopt the strategy of “pedestrianizing” streets, which consists of dedicating the whole road reserve to pedestrians and excluding motorized traffic completely. Although this approach constitutes a high motivator for urban life, i.e., it raises the function of *place* for pedestrians, from the traffic perspective it penalizes motorized traffic excessively, i.e., it breaks down the function of *movement* for motorists. Moreover, the risk is adding high traffic volumes into the adjacent road network, causing congestion.

In light of this, it may be preferred to let motorized traffic flow anyway and to redesign streets in a pedestrian-friendly manner, in order to encourage pedestrian movement and to reduce the dominance of cars without excluding them completely. *Calmed* streets, for example, make use of this principle: traffic-calming measures, e.g., street narrowing and road humps, are used in this case to make drivers slow down and to facilitate the crossing of pedestrians. Moreover, there is an alternative solution - commonly referred to as *shared space*

- in which curbstones are removed, and pedestrians, cyclists, and drivers are encouraged to negotiate their way by interacting with each other. In comparison with the *calmed* streets, which still make use of the principle of road user's *segregation*, in *shared spaces* the principle of road user's *integration* is adopted, which implies precisely the share of the same level surface.

The possibility offered by *shared spaces* to integrate all transport modes within the same space represents a great potential for traffic planning within the city centers. On the one hand, like *calmed* streets, they preserve vehicular traffic, allowing motorists to drive through (without the necessity to take alternative routes) as well as loading and unloading operations. On the other hand, like pedestrian zones, they allow pedestrians to move freely within the road reserve, without the necessity to use predefined crossing facilities to move from one side to the other.

The above-mentioned benefits in the field of traffic planning, in conjunction with the advantages provided by placemaking, have made *shared spaces* an attractive instrument for public authorities. In recent years, successful street redevelopments in accordance to the *shared spaces* design principle have taken place all over the world, whether in big towns or small villages. However, despite the lack of accordance around the instruments to judge and evaluate *shared spaces*, it can be stated that, with regard to traffic perspectives, results have not always been satisfactory.

As a way of example, the *shared spaces* realized within the EU-Shared Space Project (as part of the *Interreg IIIB-North Sea Programme*) from 2004 to 2008 are largely criticized for the lack of traffic safety in light of the analysis statistics on road casualties [38]. Moreover, citizens and associations contested the redevelopment of Exhibition Road in London in 2012 due to the lack of comfort and safety for pedestrians and cyclists [39].

As the years passed, knowledge on the subject has increased, and the basic principles for successful shared spaces have been established. In recent years, national guidelines and reports have been published, with the aim to assist traffic engineers in the design process on the basis of technical recommendations. Guidance notes on shared space design appeared in the United Kingdom [80], New Zealand [42] and Germany [10]. Moreover, technical reports reveal evidence thanks to observational data from existing schemes [9, 74].

1.1 Motivation

The above-mentioned guidelines and technical reports assist traffic engineers in the design of successful shared spaces: they guide them through the identification of objectives, help in evaluating the suitability of shared space design, and provide evidence from existing sites about road users' expected behavior. Moreover, they offer technical recommendations for scheme development and detailed design.

Nevertheless, to predict the impact of new traffic measures, traffic engineers need to compute accurate and precise results for the expected performances. This is needed to provide clear outcomes, which may help in choosing the most proper alternative and in supporting the decision-making.

The estimation of performance indicators - in case straightforward tabular methods are not employed - is performed through traffic simulation. The process consists of simulating the alternatives to the existing scenarios and to computing the measures of effectiveness (*MOEs*), which capture the goodness of traffic performance. For example, delay time is a suitable *MOE* for signalized intersections. Successively, the computed measures are translated in terms of Level Of Service (LOS) to provide an understandable result.

However, at the present time there is no methodology available to compute performances of shared spaces through traffic simulation. A method would be very helpful: Different schemes could be tested, e.g., by varying the number of vehicle lanes, the distance between them as well as extension of the shared zone. The effect of different speed limits can be investigated. Moreover, given that the success of a shared space is related to the characteristics of traffic demand, the influence of flow rate for different road users can be examined. Finally, results could be compared with conventional scenarios with space segregation and traffic rules in order to evaluate if the shared space design is suitable for the case.

In light of this, this research was undertaken to address this gap.

1.2 Problem statement

In order to create a method for shared space evaluation through microsimulation, the question must be asked: Which *MOEs* should be employed to evaluate performances? Given that performance measures reflect to some extent the aims of the traffic study, this issue can be dealt with by recalling the aims of share spaces and how they differ from more conventional traffic layouts.

Leaving aside the aspect of traffic safety, which is usually not investigated through microsimulation, shared space redevelopments are primarily focused on the improvement of pedestrian conditions. The *Local Transport Note* of the *Department for Transport* in the United Kingdom [80] refers to the improvement of pedestrian movement and comfort. The technical report of the *Bundesanstalt für Straßenwesen* (BASt) [9, 74] refers, moreover, to the improvement of the place function (which is generally related to people, in the social context, as well as to pedestrians, in the traffic context). Furthermore, focusing on the mere traffic perspective related to the movement function (i.e., to make a road user reach a destination), this aspect can be summarized with the concept of walking comfort. That means, in shared spaces a special focus is reserved to the quality of the pedestrian trip, other than efficiency aspects.

In light of these fundamental aspects, which distinguished shared spaces among other streets, the problem is how to integrate classical performance measures with the aspect of walking comfort. The matter is how to provide a mathematical formulation of this aspect, which can be computed from the result of the microsimulation.

1.3 Research objectives

The advantages of evaluating shared space performances through microsimulation is represented by the possibility to compare results with alternative conventional design (i.e., with space segregation). A stretch of road, where motorists drive longitudinally and pedestrians move from one side to the other, can be tested as shared space or as conventional design. In the first case, pedestrians can cross freely at any location and negotiate priority with motorists. In the second, crossing facilities are provided at given locations and with predefined priority rules. The same applies to intersections, which can be shared or not. If they are designed as conventional, pedestrians are usually allowed to cross at entrances, while priority among drivers has other specific regulations (right over left, roundabout).

This work focuses on the first type of shared spaces, namely, road sections without curbstones. The reason for this is that the dynamic of motion of road users follows more simple and regular patterns: drivers are physically constrained to drive longitudinally, while pedestrians cross perpendicularly, or diagonally, depending on the position of the desire line. Moreover, the interaction dynamic is more standard. To yield to pedestrians, drivers can only decelerate since deviations are not possible - the physical space is not available. To yield to motorists, pedestrians can decelerate or, at most, deviate parallel to the longitudinal direction of vehicles. This restricted number of possibilities to perform evasive actions cannot be observed in a shared intersection, where motorists also make directional changes and pedestrians have generally more alternative paths available. Therefore, with the aim to provide a method to evaluate performances through microsimulation, it was chosen to deal with simplest type of shared space. Consequently, shared intersections can be investigated in future research and via the findings of this thesis.

Two main research objectives are stated:

1. To identify suitable performance indicators for shared spaces

   Previous research has already dealt with the issue of shared space performance evaluation. In most of this research, single aspects have been considered, e.g., vehicle-pedestrian interaction [45, 43, 49], traffic safety [72], pedestrian space usage, reduction of vehicle dominance [49, 72]. In addition, other researchers have proposed holistic methods to evaluate the success of shared spaces, which take account of different aspects at once. Among them, the methodological framework developed by Karndacharuk et al. [46] is certainly the most remarkable, as it succeeded in formulating an overall performance index, which takes account of many criteria.

   However, the above-mentioned literature concerns *ex-post* evaluation methods, i.e., the street that was previously "conventionally" designed has already been redeveloped. What is actually missing is a method to evaluate the performances of shared spaces before the transformation has taken place, namely an *ex-ante* evaluation. In this regard, the main diversity is represented by the type of data to analyze, which do not come from observations in the field but should be possibly produced by microsimulation models.

   The performance indicators must satisfy two requirements: First, they must be computable from the results of microsimulation, i.e., they must be obtained through the post-processing of road users' data (the set of positions at every time step). Second, they must be translatable in terms of Level Of Service thanks to the identification of thresholds.

2. To apply the developed performance indicators on the results of traffic microsimulation of a real-world case study

   Four main steps are included within this objective. First, an existing shared space must be identified and data on the field must be collected. Second, a modeling approach for shared space, which reproduced the mechanisms of interaction between road users, must be developed. Third, the developed model must be calibrated to the real-world case study in order to provide meaningful results. Fourth, the performance indicators must be computed by simulating alternative scenarios, and the results must be provided in terms of Level Of Service.

   The main challenge is represented by the development of a microsimulation tool. In fact, at the present time, ready-to-use simulation tools for shared spaces do not exist. There is an historical reason for this: shared space design is a relatively recent topic and requires time to become regular practice. The second is conceptual: failing a method to process the output - to obtain the performance indicators and LOS - microsimulation is actually aimless for traffic studies. The third is technical: the implementation of the interaction mechanisms among road users, which occur in shared spaces, is challenging and requires high modeling efforts. For one, interaction is mostly a matter of social rules, which correspond to the logic of space negotiation, instead of compliance with traffic rules. Moreover, interaction occurs between different transport modes, which have different mechanical characteristics, operative speeds, and dynamics of motion. Finally, contrarily to classical microsimulation models, the behavior cannot be assumed as lane-based, but requires the use of two-dimensions.

Relevant scientific literature has addressed the issue of shared space modeling. The works of Bani Anvari at the Imperial College in London, United Kingdom [7, 5, 6, 4], and Robert Schönauer within the MixMe project in Graz, Austria [72] are certainly the most noteworthy. The common basis in these researches is the Social Force Model (SFM), introduced by Helbing and Molnar [36], for modeling pedestrian dynamics and extended by the authors for the shared space case. Within their works, many modeling challenges have been addressed as the path-finding problems, vehicle dynamics, car-pedestrian interactions and model calibration and validation issues. With the aim to provide a microsimulation tool aimed at performance evaluation, this research is of fundamental importance and constitutes a reference point.

1.4 Outline

The *background* of this study is provided in **Chapter 2**. After a brief historical background, the goals and objectives of shared space design are stated via existing guidelines and technical reports. This step is fundamental to clarify and to define which aspects should be captured by performance indicators. Moreover, the state-of-the-art on methods for shared space evaluation and modeling is presented with reference to the existing literature.

The process of *data collection* is documented in **Chapter 3**. A shared space street in Bergedorf, a district of the Hanseatic city of Hamburg (D), was chosen as the case study. Video recordings were carried out to capture the current traffic situation; successively, manual video tracking was performed to extract trajectory data. The aim of data collection is to provide the necessary evidence and data for the following parts of this work - from the identification of performance indicators to the development and calibration of the microsimulation model.

Chapter 4 deals with the identification of *performance measures* for shared spaces. The limits of delay time as a Measure Of Effectiveness (*MOE*) for pedestrians are discussed and demonstrated. Successively, a new *MOE*, which includes aspects of walking comfort, is developed.

The phase of *model development* is treated in **Chapter 5**. Starting from the observed behavior and movement of road users, a new social-force-based approach for simulating shared spaces is developed. The modeling framework includes an algorithm for path finding in free-flow as well as methods for handling conflicts between road users through space negotiation. Successively, the model has been implemented as part of a new simulation software, which is written in Java.

Chapter 6 presents the issue of *model calibration*. Two calibration methods are described: first, a microcalibration method, which takes single interaction situations as the ground-truth for calibration and returns an optimized set of parameters through mathematical methods; second, a macrocalibration method, which considers performance indicators aggregated over time as reference values to adjust model parameters.

Alternative scenarios are tested in **Chapter 7**. First, the reference case study is simulated with a conventional design, i.e., standard crossing facilities for pedestrians. Successively, shared space scenarios are tested with different traffic demand and different extensions of the shared zone. *MOEs* are computed and discussed with respect to the reference scenarios. This step is called *alternative analysis* and provides the results of this work.

Final remarks and considerations are given in **Chapter 8** with an outlook on future research.

2 Background

Urban streets play a multifaceted role in our cities. As traffic environments, they have to ensure the movement of all road users - motorized and non-motorized - in order to accommodate travel from one place to another, safely and efficiently. This is called *movement* function. As public environments, they are the core of the social and public life and serve as places to meet people's needs, i.e., living, working, socializing, and moving around. This is called *place* function. Both functions make our streets not only mere traffic facilities to reach a certain destination but also the destination in themselves. [79].

In the planning and design process, the street character type is determined by the relative importance of its *movement* and *place* functions. Defining this relationship is fundamental for the choice of the most suitable design principle, i.e., *segregation* or *integration*.

Segregation Different types of road users are spatially separated from each other when traveling toward the same direction. The carriageway is dedicated to motorized vehicles, while cyclists and pedestrians have separate lanes, which cannot be invaded. In the case of crossings, traffic flows are separated on a temporal level by control devices such as markers, signs, and traffic lights, which define priority rules.

Integration A portion - or the total - of the street space is shared by different types of road users, who move on the same surface with no level difference. This approach is usually referred to as *integrated street design* and is beneficial when the function of place is relevant.

Note that these design principles are also defined in the German "Guidelines for Urban Road Design" (*Richtlinie für die Anlage von Stadtstraßen* [77]), respectively, under the keywords of *Trennungsprinzip* and *Mischungsprinzip*.

The principle of road users' segregation is reasonably preferred when the function of movement is predominant. In this case, preserving high Levels of Service - and consequently, high operative speeds - makes it necessary, especially for safety reasons, to reserve separated parts of the road for the different types of road user with the purpose to minimize traffic conflicts. In the course of this dissertation, when the design implies physical separation, it will be referred to as *conventional* design.

Instead, road users' integration is more suitable when the focus of design is on pedestrians and their needs. In the absence of predefined crossing facilities, pedestrians would move freely around the space, from one side to the other. This factor increases the perception of the street as a public space. Moreover, the absence of curbstones and physical barriers preserves space flexibility. By integrated street design, motorists are assumed to become more attentive and prudent due to the possibility of injuring pedestrians.

After briefly introducing the basic concepts that underpin shared space design - i.e., the place function of streets and the principle of road users' integration - the research background of this dissertation is provided in the next section. This includes a historical contextualization that focuses on the origin and development of the shared space concept (2.1). Successively, shared space design is discussed with respect to goals, objectives, and instruments (2.2). Furthermore, the state of the art on shared space performance evaluation is provided (2.3). Finally, the modeling issue is treated by identifying modeling challenges, previous research, and the mathematical formulation of the social force model (2.4).

2.1 Historical background

The origin of the concept of street sharing arrived with the advent of horse-drawn vehicles in the urban environment. However, the "forced" sharing of street space with coaches and carriages soon became a threat to pedestrians. The advent of the automobile has successively increased the concern for safety and has oriented road design toward the principle of road users' segregation.

The concept of space sharing can be found in the Dutch *Woonerven*, which are residential streets designed for promoting a sense of place. They represent the first application of the concept of multifunctional roads, as theorized by Sir Colin Buchanan in *Traffic in Towns* [19]. Successively, the concept was exported to the urban context in two different forms: *calmed streets*, i.e., streets with elements of traffic-calming aimed at reducing vehicle dominance, and *shared streets*, i.e., streets with a single level surface where all road users are encouraged to interact by space negotiation.

2.1.1 Pre-automobile era

The appearance of our urban environment has evolved over time according to societal characteristics, and has been continuously redesigned in response to the changing needs, values, and current desires of the population.

Cities were originally "walking" cities, in which citizens could interact and practice social life essentially by foot. In the Middle Ages, large city squares served as meeting places and open markets, surrounded by public buildings, e.g. churches and city halls. Around these "places for interaction", a set of narrow and unpaved streets spread around, providing access to buildings.

The advent of horses as a means of transport coincides with the first threat to the movement by foot. The aristocracy rode on four-wheel carriages and coaches; for the middle class, buggies (e.g., private horse-drawn vehicles) were employed. To accommodate poor workers, horse-drawn railed vehicles (also known as streetcars) were introduced, commonly considered the first form of public transport in the cities. Despite their slow operation speed (carriages moved at about 10 km/h), it became more difficult for pedestrians to walk the streets and feel safe. This led to the construction of sidewalks to safeguard pedestrians and by keeping them away from busy carriageways [31]. It therefore follows, as already in the beginning of the nineteenth century, the necessity to protect vulnerable users as well as to ensure the undisturbed flow of horse-drawn vehicles was addressed by setting up different spaces for different types of road users.

In the second half of the 1800s, large cities were dealing with the problem of crowded and unhealthy medieval-era neighborhoods. To contrast this tendency, it was necessary to demolish large parts of the historic city to create better housing, open spaces, and water and sanitation infrastructures as well as to open new squares and avenues. In this context, the Haussmann's renewal plan in Paris during 1850-1870 became the most influential in the world. The plan included a redesign of the whole city in response to the requirements of modern life, in particular to increased traffic [11]. On the one hand, major streets were constructed to allow for easier circulation of horse-drawn vehicles. The *Croisée de Paris*, for example, is the most remarkable and consists of a great cross in the center of Paris, which permits easier connection from east to west. On the other hand, new large boulevards, parks, squares and gardens were created, which constituted public places for pleasurable walking. Within the boulevards, the street sides were designed exclusively for pedestrians, while the carriageway in the middle was both for pedestrians and horseback or carriages [31]. The Avenue de l'Opéra, created from 1864 to 1879 as part of Haussmann's renovation of Paris, is an ideal example of this innovative design approach. As shown Camille Pissarro's painting (Fig. 2.1), these wide carriageways absolved both the movement and the place function, allowing the interaction among people with the flow of horse-drawn vehicles. Successively, the "Haussmannian model" was applied in many other cities across Europe such as Berlin, Vienna, and Rome.

With the steady increase of horse-drawn vehicles and the introduction of bicycles, at the end of the nineteenth century, cities became congested environments in which various types of road users were sharing the street together chaotically. Under these circumstances, the advent of automobile worsened the current situation and created more traffic congestion.

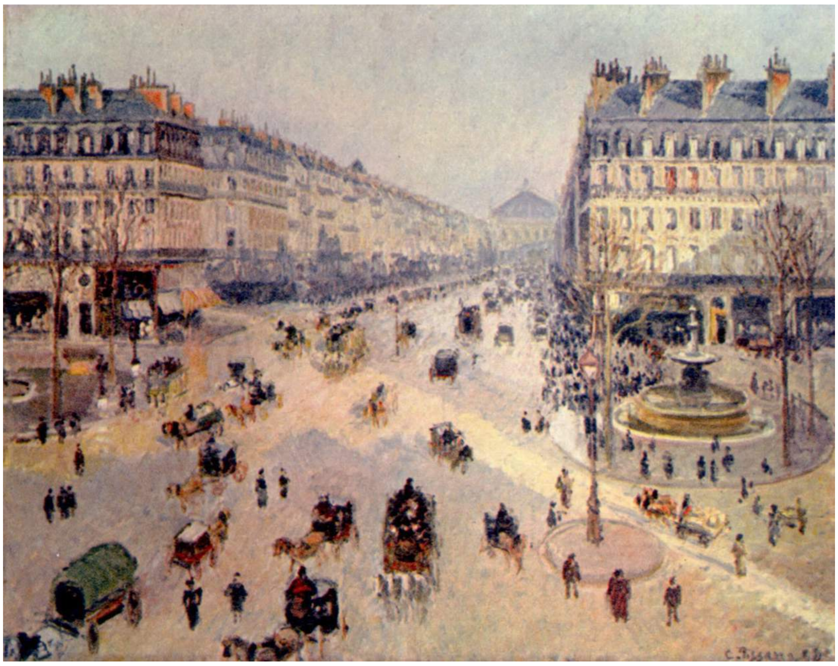


Fig. 2.1. The avenue de l'Opéra, created by Haussmann, painted by Camille Pissarro

Given the lack of dedicated infrastructures, motorized vehicles were hosted within the existing street space, which came to represent a major safety concern, since motorized vehicles operated at higher speeds, had strong body structures, and took up more physical space. Moreover, parking spaces and traffic management tools (e.g., traffic signals) were missing. In other words, the use of streets as social and recreational gathering places was threatened and indeed supplanted by the requirements of increasingly rapid vehicular traffic [84]. Beyond the increase in road congestion and safety concerns, automobiles also brought a wide range of negative side effects, e.g., increased pollution, gasoline, and oil use. As a consequence of the disruptive advent of motorized vehicles, urban planning in the first decades of twentieth century responded by providing them with more and more street space, in order to reduce congestion and increase traffic speeds, which in turn encouraged additional automobile usage.

2.1.2 The Buchanan Report

The exponential growth of car ownership in the 1950s and 1960s led to increased traffic congestions in towns, with a consequent worsening of the urban street environment. The potential destructiveness of motor vehicles was first foreseen by architect, civil engineer, and urban planner Professor Sir Colin Buchanan in the early 1960s, who was appointed by the Ministry of Transport (UK) to lead a Working Group with the aim "to study the long-term development of roads and traffic in urban areas and their influence on the urban environment". The results of this investigation are included in the book *Traffic in Towns* [19] published in 1963, also known as *The Buchanan Report*, which is universally acknowledged as a cornerstone in the field of traffic planning.

The novelty of the report is represented by the recognition of increased car traffic inside urban areas ("fast, heavy, and dangerous vehicles"), which would have strongly affected the comfort and safety of pedestrians through noise, pollution, vibration, and visual impact.

Buchanan did not offer a clear design solution to prevent the dominance of car traffic. Nevertheless, he stated the need for a turning point in urban design criteria in towns, which he outlined in Chapter 2, "The Theoretical Basis", by introducing the duality of a *network of roads* and complementary *areas of good environment*. The first ones accommodate the movement of motorized vehicles and consist of a network of routes across and around the city. The second ones host social lives ("they are areas of group of buildings [..] in which daily life is carried on"). Within them, vehicular traffic should be subordinated to the environment, in particular by setting a maximum acceptable level of traffic. In this sense, Buchanan proposed that mixed use is possible but only "up to a point, a mixture of pedestrians and vehicles is not seriously harmful" [19].

With the aim of this dissertation, the importance of The Buchanan Report is represented by the theorization of multifunctioning areas, which accommodate the movement and the place function of streets at the same time.

2.1.3 The Dutch "Woonerf"

The first application of the multifunctional environmental areas theorized by Buchanan can be found in the Dutch *Woonerf* - also *home zones* or *residential yards* - which appeared in the late 1960s in the city of Delft (NL) thanks to the road design experiment of the Planning Department of Delft. The *Woonerven* responded to the need to integrate vehicular traffic in residential spaces by ensuring comfort and safety for the residents as well as sense of place for the community. The multifunctionality of these areas covers in this sense the function of movement as well as access to buildings and parking and place.

From the street design perspective, the *Woonerven* included a single surface shared by different types of road users as motorists, pedestrians, and cyclists, where curbstones and road markings are removed - or at least minimized (see Fig. 2.2). Streetscape elements are encouraged, as vegetation, benches, and bollards, which serve as a traffic-calming measure but also increase the sense of place. Moreover, different areas function as carriageways, in the middle, and comfort zones, at the roadside, and are demarcated informally through different pavement colors.

Fig. 2.2. Example of Dutch Woonerf

The success of these street experiments led to official recognition by the Dutch government in 1976, which assigned *Woonerven* a legal status and integrated them into road traffic regulations [13]. Traffic hierarchy was reversed; in the *Woonerven* pedestrians were assigned priority over vehicles, and the last were also imposed to drive at walking pace. Moreover, pedestrians were allowed to practice social activities on the street space. Children, for example, were allowed to play on the street on the condition that they must not impede vehicle passage.

The experience of the *Woonerven* is historically and conceptually necessary for the shared space design for two main reasons. First, it represents the first application of multifunctional street space, i.e., theorized, experimented, and finally legally recognized. Second, many physical elements of integrated street design, as the single surface concept and the minimization of road markings, were applied and tested for the first time as a concrete measure for achieving comfortable and safe coexistence between different types of road users.

2.1.4 Urban context: calmed and shared streets

The innovative design developed with the *Wonerveen* found applications thereafter in towns, villages, shopping streets, and town centers [63]. From a conceptual point of view, it can be seen as a shift from a residential context, with an overwhelming access function, to an urban one, with a preponderant place function. Indeed, while in residential areas the street was a destination itself - i.e., for the residents - in the urban context, the street also had to become a destination for those who do not live in the area. This is usually encouraged via retail, bars, restaurants, seats, and activities or amenities for young people, in order to attract people and create a sense of place. As a consequence of this new role, the street design must remain in accordance with the public function of the space.

The adaptation of the *Woonerven* concepts to the urban context can be basically classified into calmed and shared streets [47]. The first ones adopt the features of the *Woonerven* as traffic-calming techniques. Street furniture, vegetation, street narrowing, informal markings, and other measures are used to influence motorists´ behaviors, provided that the carriageway is physically separated from the sidewalk by curbstones. For example, note how in Fig. 2.3 traffic-calming techniques, e.g., pavement, vegetation, are employed to increase the prudence of motorists. The second ones, besides traffic- calming measures, implement the continuously paved and curbless surface design - road users´ integration, indeed. The Exibition Road in London is shown in (Fig. 2.3 b) as an example of integrated street design.

Fig. 2.3. Calmed street in Amsterdam (left), shared street in London (right)

Both calmed and shared streets, despite the different approaches, can be defined as "pedestrian-friendly" for their contribution to more liveable and walkable communities as well as safer and more comfortable urban spaces. Alternative strategies like "pedestrianization" can also help with this matter but with the great disadvantage to exclude car traffic completely, thus deleting a traffic corridor and cutting down the function of access.

With respect to the residential context, the urban calmed and shared streets imply a higher challenge in comparison with *Woonerven*. Given the urban context, and no longer being residential, higher traffic volumes may be involved. Traffic is not only generated by those living around but is also driving toward other destinations. This makes it necessary to adapt the street design to the new context in order to ensure good quality of traffic as well as safety.

2.2 Aims of shared space design

At the beginning of this chapter, the main functions of streets - movement and place - were mentioned and explained. The first is related to the circulation of traffic. Preserving the movement function means to ensure the flow of vehicles with safety and quality. The second is related to the interaction, exchange, and other social and civic activities that take place within public spaces of cities. Preserving the place function means to ensure a pleasant sojourn of people´s encounters and exchange. In light of this, shared spaces have to be regarded as areas where the balance is redressed in favour of the place function although not necessarily at the expense of movement [80]. This means that place function has to be considered as the key objective but without penalizing quality and safety of traffic.

This dissertation focuses solely on the function of movement of shared spaces. Traffic quality and traffic safety are discussed and investigated, and performance measures will address the movement of road users only. Moreover, the definition of the aims of shared space - the object of this section - will consider this focus accordingly. However, for the sake of completeness, and given the multidisciplinary of this issue, the aims connected to the place function will also be briefly discussed in Sec. 2.2.1.

In this section, the issue of shared space aims is first dealt with by discussing the ultimate aims, referred to as *goals* (Sec. 2.2.1), and after by identifying the sub-aims, referred to as *objectives* (Sec. 2.2.2). Moreover, the *instruments* available for the achievement of objectives - in the field of street design and traffic control - are discussed (Sec. 2.2.3). This classification is aimed at examining the inter- and intra-dependency among goals and objectives as well as the connection between measures to implement (i.e., instruments) and the achievement of shared space aims. In order to do this, guidance notes on shared spaces from the United Kingdom [80], New Zealand [42], and Germany [10, 9] will be used as a reference. Despite these guidance notes referring to a quite different context and using different approaches, nevertheless, here we aim to find common ground and similarities.

The Local Transport Note 1/11 “Shared Space” [80] was published in 2011 by the Department for Transport of the United Kingdom to provide guidance for local authorities in using the shared space design principle. They are historically significant, as they are the first official guidelines on shared space edited (or commissioned) by a governing body in the world. In terms of contents, they state key principles for street sharing and provide useful information to practitioners for implementation.

The Guidance Note “Shared Space in Urban Environments” [42] was published in 2012 on a grant from the Institute of Professional Engineers New Zealand (IPENZ). It is based on the findings of a study tour undertaken in Europe to study shared spaces and contains recommendations for the implementation of shared space schemes in New Zealand’s urban town center environments. This guideline was chosen for the clear and synthetic formulation of objectives and design principles.

In Germany, the Road and Transport Research Association (Forschungsgesellschaft für Straßen- und Verkehrswesen, FGSV) published in 2014 a guidance note called “Hinweise zu Straßenräumen mit besonderem Querungsbedarf - Anwendungsmöglichkeiten des Shared Space-Gedankens” (lit. Recommendations for streets spaces with high crossing demand - Application of the shared space principle) [10]. Moreover, the Federal Highway Research Institute (Bundesanstalt für Straßenwesen, *BASt*) published a report called “Einsatzbereiche und Einsatzgrenzen von Straßenumgestaltungen nach dem Shared Space-Gedanken" (lit. "Areas and limits of application of street design according to the shared space principle") [9]. Both reports provide reference material for designing shared space schemes in Germany: The guidance note of FGSV focuses on basic principles and conditions for the feasibility of shared streets, which are useful in a preliminary phase. The *BASt* report offers detailed analysis of a series of shared spaces already existing, with a collection of data about traffic volumes, traffic conflicts, accessibility, and the quality of sojourns. These publications were chosen for the geographical context of this research as well as for the focus on pedestrian crossing.

To the interest of clarity and readability, a conceptual framework of goals, objectives, and instruments for shared space design is provided in Fig. 2.4. To show inter- and intra-connections between boxes, arrows are provided with an alphanumeric identifier on the side, which is also recalled in the text.

2.2.1 Goals

Total consistency is lacking among guidance notes in shared space goals definition. In the Local Transport Note [80], the improvement of pedestrian movement and comfort is mentioned as the key objective of shared space design. That means the redevelopment of streets with shared space design must primarily - and positively - have an impact on pedestrian conditions, providing more and better possibilities to move around despite the presence of vehicles. The German *BASt* report [9] also identifies this aspect as a primary objective via the words "improvement of the quality of sojourn" and "increase of attractiveness of the place", but it is presented at the same level of safety issues ("improvement of traffic safety"). In this respect, shared space design is assumed as an alternative approach to calm streets and to reduce crash rates. Finally, the Guidance Note of New Zealand [42] presents a list of six key aims: Besides economic and urban design aspects, the focus is on pedestrian condition ("improve pedestrian amenity"), vehicles dominance ("reduce vehicle speed and volume") and safety ("reduction of crash rates").

With the purpose to define a common basis among different guidance notes, in this work two major aims are identified, i.e., the improvement of pedestrian condition and traffic safety.

The concept of "pedestrian condition" in the guidance notes can be interpreted via two facets. The first is related to the "place" function, i.e., the quality of sojourn (see Sec. 2.2.1). The second is in regard to the movement function and is linked to the quality of the trip, i.e., reaching the destination. Shared spaces must improve the movement and comfort of pedestrians [80] and to allow them to move freely around the space [42]. High-quality trips imply that pedestrians freely choose the preferred trajectory and speed, while not

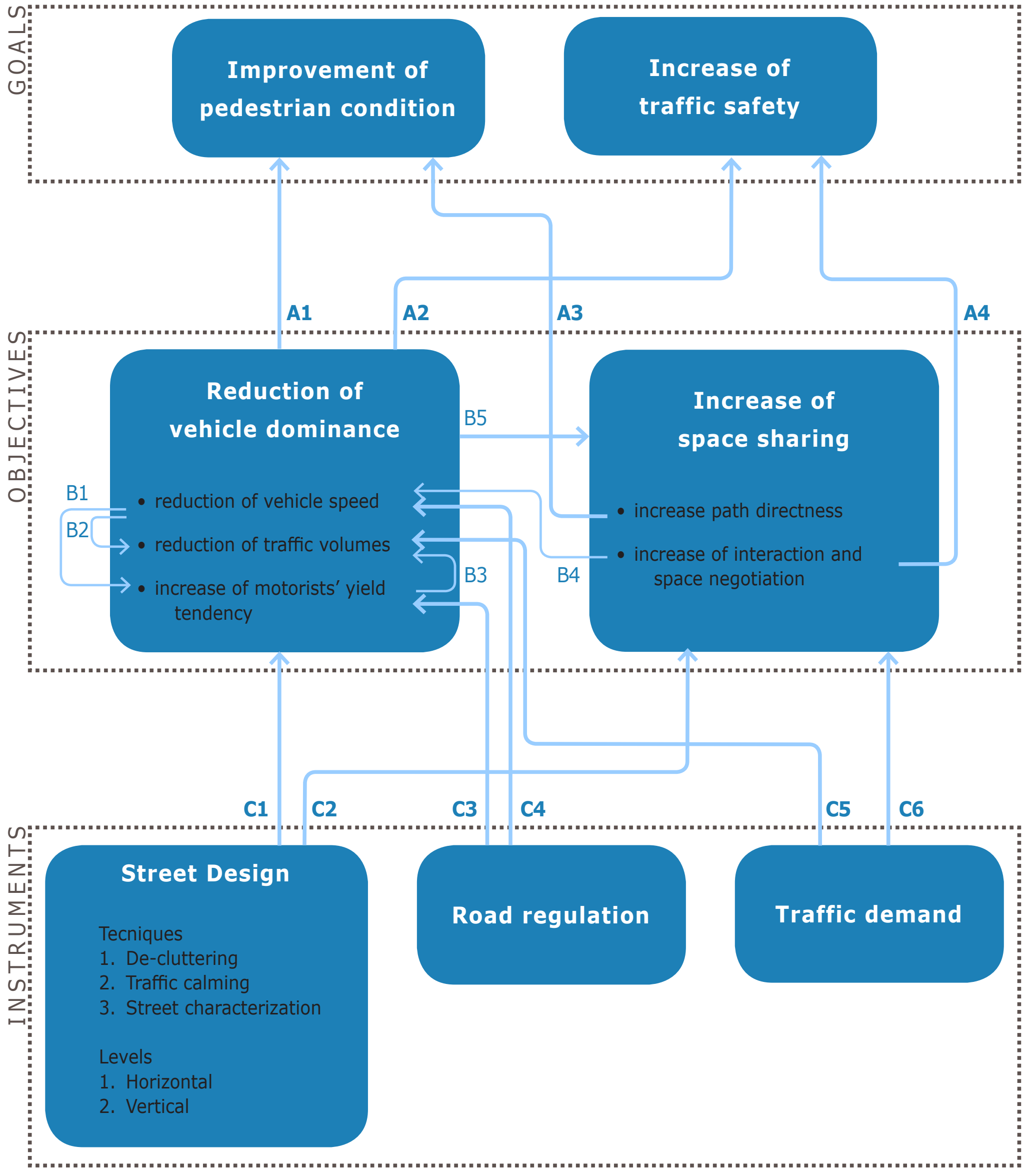


Fig. 2.4. Aims, objectives and instruments of shared space design

being threatened by the presence of vehicles. Moving from one side to the other of the road reserve must occur without predefined crossing locations but at the pedestrian's own choice.

Shared space design is also aimed at improving traffic safety. However, considering the principles of shared spaces, this statement could appear to be contradictory. Logically speaking, one might think that removing curbstones and encouraging free interaction would worsen traffic safety, just because conflicts between road users would become sort of "unregulated": they would occur within an extended area - not a restricted one, e.g., via by pedestrian crossings - and without the support of clearly defined priority rules. Nevertheless, the key of interpretation is the increased responsibility of road users, which are asked to interact with each other via the principle of space negotiation. This means that the design itself should lead to a state of alert, which makes road users behave more prudently, especially motorists. This phenomenon is attributable to the psychological theory of the "risk compensation" and is discussed in Sec. 2.2.3.

Other goals

Within shared streets, as in any other public space, people are expected to practice a wide range of activities, which are usually defined as "social" since they are related to the presence of other people and because they imply interaction. They may include children at play, conversations, communal activities, e.g., markets and social events, and also passive contacts as simply seeing and hearing other people [27]. In this respect, there is a social objective in designing public realms, namely, to attract people and increase the sojourn within the area. Moreover, spending time outside of private buildings was demonstrated to improve public health and encourage walking. There is also an economic purpose, which consists of supporting local economies and attracting business investments [64]. Summarizing, the design of a shared street as a public space must account for social and economic aspects, aimed at promoting sojourn and human interaction, possibly via spending money on adjacent activities. Indeed, guidelines recommend to create "pleasant environment for pedestrians", which makes the street "a place to visit and to spend time" [42], as well as spend money.

In this regard, two essential features are typically recommended to design successful places: space flexibility, on the one hand, to allow a multitude of simultaneous functions to occur, and where space can be redistributed at different times and used for specific events as street markets or stands to promote initiatives [42]. On the other hand, the space design must provide adequate street furniture to support space usage, e.g., seating elements, lighting, fountains, and public art [85].

2.2.2 Objectives

Shared space goals, as they are formulated in Sec. 2.2.1, are difficult to quantify; further, they require more tangible and measurable sub-aims in order to be achieved. Here, these are called *objectives* of shared space and, in light of existing guidelines, can be gathered under two main concepts: the reduction of vehicle dominance, on the one hand, and the increase of space sharing, on the other. The possibility to measure them, as will be explained in Sec. 2.3, has led researchers to build performance indicators around these two concepts, with the purpose to evaluate the success of shared space design.

Vehicle dominance

The reduction of motor vehicle dominance is defined by the Local Transport Note [80] as "the" key factor to achieve the shared space design. Three main aspects, quantifiable and directly measurable, can be identified under the concept of vehicle dominance: the traffic volume of vehicles (measurable e.g. in veh/h), the speed of vehicles (measurable, e.g., in km/h), and also the tendency of drivers to yield for pedestrians, (which can be measured by a yielding rate in percentage, considering all traffic conflict occurring between motorists and a pedestrians).

These aspects are strongly related with each other. Further, there is evidence that reduction in vehicle speed encourages drivers to yield to pedestrians (arrow **B1**). Bertulis et al. [16] studied driver behavior at unsignalized intersections and observed that "the higher the motor vehicle speed, the lower the yield rate". Moreover, the Local Transport Note [80] stated that "as speeds reduce, drivers increasingly give way to pedestrians". Driving by lower speed and giving way to crossing pedestrians inevitably lead to increased travel time. Consequently, the attractiveness of the traffic corridor is reduced, which may result in decreased traffic volume in the long term (arrows **B2** and **B3**).

The reduction of vehicle dominance brings concrete benefits in term of improvement to pedestrian conditions (arrow **A1**). Indeed, the reduction in traffic volumes generates less noise and less pollution, including CO_2 emissions. Moreover, it frees up space for pedestrians, thus allowing these to move more freely and reducing the necessity of path deviations. Together with speed reduction, this factor positively affects human perceptions of a calmed environment: Pedestrians would feel to be in a public space, rather than a traffic corridor, with higher comfort sensation. Finally, the increase in yielding rates would facilitate the crossing of the road for pedestrians, thus reducing decelerations and deviations.

Traffic safety would also benefit from the reduction of vehicle dominance (arrow **A2**). As will be explained in Sec. 4.2, traffic conflict techniques are typically used in transportation safety studies, since observing collisions would be unfeasible. In light of this, the reduction of traffic volumes directly reduces the overall number of conflicts, as a consequence. In addition, the increased tendency to yield would reduce the conflict severity, since the vehicle would brake in advance without moving on in the process of space negotiation. Last, the reduction of vehicle speed would lower the severity of the potential collision. The reason is that the higher the vehicle speed, the shorter the time available for a driver to stop and avoid a crash [62]. In support of this, Kröyer discovered a relationship between the mean travel speed of vehicles and the injury severity and risk of fatality [50]. Moreover, many studies have traced the relation between pedestrian fatality risk and the speed of vehicles. An exemplary work was carried out by Pasanen et al. [57] within a safety analysis in the city of Helsinki, which revealed that pedestrians have a 90% chance of survival when struck by a car traveling at 30 km/h or below but less than 50% chance of surviving an impact at 45 km/h.

Space sharing

In shared streets, as the name suggests, sharing the space is a crucial factor for the success of street transformation. Sharing is defined by the Local Transport Note [80] as "the ability or willingness of pedestrian, facilitated by the sympathetic behavior of motorists and other, to move freely around the street". It is also "a measure of how well pedestrians are able to use the space as they wish without having to defer to vehicle users". Two aspects can be identified.

The first is the path directness, which expresses the deviance between the desire line, i.e., direct line between origin and destination of a trip, and the undertaken path. The idea behind this is that, if sharing effectively takes place, pedestrians would "use the space as they wish to", i.e., they would cross the area dedicated to the flow of vehicles according to preferred speed and trajectory, without necessarily yielding to motorists. When the deviance between desire line and undertaken path is low, the trip has been accomplished without excessive detours. When deviance is high, it can be assumed that the interaction with vehicles has forced the pedestrian to modify his/her preferred behavior. This leads to time delay in reaching the destination as well as physical discomfort for the necessity to turn one's direction and modify the walking pace. It can be concluded that minimizing the need of detours leads to the increase of space sharing and, consequently, to the improvement of pedestrian conditions (arrow **A3**).

The second one concerns the interaction between motorized and vulnerable users, namely, situations where one of the interacting users modifies the expected behavior to avoid the collision. These events are the core of shared space design and have to be promoted and encouraged. In this respect, failure of shared space design is directly observable when pedestrians do not look for interaction but prefer to cross only in the absence of vehicles, which would lower the number of interactions, or when they cross the carriageway area at specific locations, which would restrict the area of effective interaction. A high number of interactions, uniformly distributed over the street, is not only a sign of pedestrian confidence with the space but has a positive implication of traffic safety. This fact was demonstrated within a safety performance study in shared streets in New Zealand by Karndacharuk et al. [49], who inspected the relationship between the number of interactions and operating vehicle speeds. The authors found that “the more interaction there are, the lower vehicle speeds are” (arrow **B4**). This would result in decreased kinetic energy and likelihood of injury severity in the event of a crash, which reveals a connection between the number of interactions and traffic safety (arrow **A4**).

There is also another fundamental reason why traffic safety would benefit from high interaction rates. Space negotiation, by definition, is the dispute of priority. That means, despite traffic rules, which may have been defined within the road section, they are somehow called into question and not totally complied with. For example, a driver who gives way to a pedestrian as a courtesy, even if he/she has the right of way, is a sign that interaction is actually taking place. Further, calling traffic rules into question implies increasing the state of alert, to behave more prudently, to be aware of risk and to be ready for it. In line with this thinking, via more attentive road users, traffic conflict severity is expected to sink, which translates into increased traffic safety and lower probability of collision.

In conclusion, it must be noted that the reduction of vehicle dominance increases pedestrian confidence, which means more direct paths and more availableness to negotiate the space (arrow **B5**).

2.2.3 Instruments

Given the objectives of shared spaces, as explained in the last subsection, the question is which instruments are available for traffic engineers to achieve them. In this work, four main instrument classes have been identified, i.e., street design, road regulations, transportation planning, and placemaking. It must be reminded that, as past experience on shared spaces has highlighted, the achievement of objectives is possible only through the joint action of different instruments.

Street design

Traffic engineers typically have two complementary approaches to influence the behavior of road users within the street, i.e., by rules or by design. The first is based on road regulation and consists of legally imposing traffic rules, with the threat of a fine if the rule is disregarded (this instrument is covered in Sec.2.2.3). As a way of example, one may consider the imposition of a speed limit on a road section. However, this strategy works only if road users consider the risk of being caught as great enough to encourage modification of the behavior [55]. Moreover, restrictions might not be successful if there is a discrepancy between the imposed behavior and the perceived level of risk. For this reason, street design must complementary operate. Martens et al. [52] remarked that, in the case of speed limit, the key is to design roads that are "self-explaining". That means, the road must provide a speed image in accordance with the imposed speed limit, so that drivers adapt the driving speed more or less automatically. This was also remarked by Abele and Møller [1], who recommended traffic engineers to design "predictable" roads, which directly suggest the expected and more appropriate driving behavior.

The concept behind shared streets actually goes further: the street design is not complementary to road regulation but is the main instrument to, informally, communicate to road users the expected behavior. Street design has the main task to reduce vehicle dominance, on the one hand (arrow **C1**) and to encourage space sharing, on the other hand (arrow **C2**). The Local Transport Note [80] remarks that, as a general principle, shared space should present "a series of features and events to drivers that require them to increase their awareness and make them conscious decisions on how they should negotiate each feature". The technical report of *BASt* [9] also claims that evidence has shown that "when street is design by the shared space principle, motorists tend to drive more slowly and renounce to the total priority over pedestrians".

Traffic engineers in the field of street design can generally employ the three main techniques to accomplish shared space objectives, which are explained in the following paragraphs.

De-cluttering consists of reducing the use of signs, markings, and traditional features used to demarcate space, such as curbstones, with the aim to make road users more self-responsible.

Traffic-calming is aimed at reducing the negative effects of motor vehicles and improving conditions for non-motorized users. It can be applied by a wide range of physical measures, e.g., visual narrowing, tight geometry, and horizontal deflection.

Characterization makes the street look different from conventional ones, so that drivers perceive the diversity and behave more attentively. It is achieved by changes in surfacing, by street furniture in unconventional positions, by vegetation, and by demarcation of entrance zones.

The term "de-cluttering" literally means to reduce clutter on the road reserve by removing traditional physical elements used to separate different areas. According to the conventional design based on road users' segregation, vehicles and pedestrians are separated by a level difference, which clearly identifies a carriageway and sidewalk. In this way, traffic conflicts between different types of road users are minimized, and pedestrians feel more protected. However, this practice will decrease motorists' risk perception, leading them to drive at higher speeds. This has two negative implications: first, it penalizes pedestrian activities on the roadside because of noise and pollution; second, it may lead to safety problems at unsignalized intersections.

In the 1980s, Dutch traffic engineer Hans Monderman, who is commonly referred to as the father of shared space design, challenged the idea that only the principle of segregation could ensure traffic safety. As a road safety investigator in the town of Oudehske (NL), Monderman experimented with new design approaches where features to demarcate space were removed, along with signs, road markings and street furniture. This resulted in flat surfaces throughout all the road reserve, where travelers were forced to share the space and consequently, negotiate right-of-ways amongst themselves [65]. The results on traffic safety were remarkable and even exceeded Monderman's own expectations. The removal of curbstones, traffic lights, signs, crosswalks, and lane markers indeed had encouraged drivers to be more prudent and cautious. The removal of traditional features used to regulate traffic had the effect to empower road users, i.e., the "transfer of power and responsibility", as defined by Monderman himself. Without the support of conventional features, drivers were asked to behave as they want to, but at their own risk.

This concept, experimented by Monderman in the road context, goes back to the theory of "risk compensation", which states that people adjust their behavior to the perceived level of risk. When people perceive greater risk, they act more cautiously; when they feel more protected, they act less carefully. In this sense, when risk is high, people compensate for that risk by behaving more prudently. However, this theory is often debated and, to the best of our knowledge, has not scientific foundation. Hedlund [32] investigated risk compensation theory in order to find evidence for and against its claims; he found that behavioral adjustment may occur in some cases but not in others. Moreover, the adaptation to more or less safety measures is difficult to measure. Nevertheless, with or without a scientific foundation, Monderman has shown in practice that the removal of traditional safety features aimed at regulating traffic and separating users might, paradoxically, increase traffic safety. This was also observed within other traffic experiments or pilot projects, in which traffic lights were removed and traffic performances, on traffic quality and safety, did not necessarily worsen [22, 73]. So, finally, the de-cluttered design makes use of this mechanism of increasing the perceived risk, which is aimed especially at making drivers more prudent and attentive.

Traffic-calming consists of implementing specific design measures aimed at reducing drivers' speed and generally to improve traffic safety. These measures are largely used in shared streets with the purpose to make it physically difficult for motorists to drive through quickly [80]. It can be achieved by implementing street narrowing: physically, by making the carriageway area tighter, or visually, by adding, e.g., a row of trees at the roadside (which also improves the sense of place). This helps in reducing driver speed as well as improving the facility to cross for pedestrians. Horizontal deflection can be used by creating a meandering route through the space. Moreover, vertical deflection is usually implemented at the transition zones to lead drivers to enter the shared zone via appropriate speed. Finally, road design must reduce forward visibility by features such planting, parked vehicles and public art. These typical traffic-calming measures are employed in shared spaces with the aim, again, to reduce vehicle speed. However, as proof that the whole issue is like chasing one‘s tail, it is noted that the same Department for Transport, in the Local Transport Note “Traffic Calming” [81], has addressed “shared road space” as a measure of traffic-calming. This means that it is not only true that lower speeds promote interaction, but also that it‘s contrary, i.e., sharing makes drivers slow down.

Street designers recommend to characterize shared space in order to make it look and feel different [80]. Change in surfaces is strongly advised, since they were found to effectively reduce traffic speed (between 4 and 7 km/h according to the Manual for Streets [79]. Moreover, vegetation, cycle parking, or other items of street furniture in unconventional positions can help to differentiate and personalize a street.

The techniques described until here can be obtained by the joint deployment of different levels of design, which reflect different levels of intervention. There is *horizontal design*, which consists of the allocation of spaces, namely, the scheme. Moreover, there is *vertical design* which includes the disposition of street furniture and other vertical elements. Finally, the *surface design*, including materials and road markings, constitutes a valid instrument to influence road users’ behaviors.

Horizontal design, namely, the subdivision of spaces, is the first level of design. This includes, first, defining along the road section where the shared zone must start and end; second, the *comfort zone* of pedestrians (where vehicles are not supposed to drive); third, additional features like position of parking, for vehicles and bicycles, and vegetation. The allocation of spaces is needed to define where the interaction has to take place, where pedestrians are expected to cross and where drivers are supposed to reduce their speed and drive attentively.

Vertical design, as street furniture, can also be used to achieve de-cluttering, traffic-calming, and street characterization. This includes single elements, e.g., bollards, streetlamps, benches, vegetation. Further, Karndacharuk et al. [46] recommended, for example, the strategical placement of street furniture. The Local Transport Note [80] remarks that the use of them must be justified, and “it is good practice to aim for each item to serve more than one purpose”.

Further, the choice of surface materials and paving colors is part of street design. However, despite evidence showing the effectiveness of many measures, it is difficult to estimate how far they are able to influence road users' behavior.

Road regulation

The concept of shared space is often misidentified with the removal of traffic rules. This stems directly from the media clamor that Monderman's design experiments have generated, which were portrayed by the impressive theory that traffic signs are not really necessary in our road environment.

Nevertheless, the core of shared space design is not that traffic signs (and all other "formal" indications) are unnecessary but rather that street design is much more important in influencing road users' behaviors. Road regulation is necessary indeed for three main reasons: First, it can provide information that design cannot provide (e.g., the "no entry" sign); second, it can communicate, indisputably and unquestionably, that the violation of a traffic rules has implicit consequences; finally, it is necessary to blame road users in the case of accidents and, consequently, to guide insurances in the award of damages. In addition, it must be reminded that, within national laws, renouncing traffic rules could be ineligible, i.e., this is the case of Germany [10].

Types of road regulation for shared streets can be classified into two major categories: pedestrian priority and vehicle priority. In the first case, priority is assigned to pedestrians, while cars have to adapt their behavior accordingly by giving way (arrow **C3**). In the second case, motorized traffic has priority over pedestrians, who must yield. Speed limits are usually set up to calm traffic (arrow **C4**).

In the case that vehicles have the right of way, usually a simple speed limit is set. In the German highway code, this is implemented by the sign 274.1 "Verkehrsberuhigter Geschäftsbereich" (lit. "traffic calmed shopping area") in which a 20 or 30 km/h speed limit is prescribed.

Alternatively, when pedestrians have the right of way, vehicles have to be penalized more intensively. In the German highway code, this is implemented by the sign 325.1 "Verkehrsberuhigter Bereich" (lit- "traffic calmed area"), commonly, and improperly, called Spielstraße (lit. "play street"), which is the equivalent of the "Home Zone" in the United Kingdom. According to this regulation, pedestrians are allowed to use the street in the whole extension but must not impede the passage of vehicles. From their side, drivers must drive at walking speed and not endanger pedestrians.

Traffic demand

Traffic engineers can also intervene on traffic demand to achieve successful shared spaces. On one hand, the volume of expected vehicles can be reduced. On the other hand, pedestrian presence must be increased.

The transformation into a shared space discourages drivers to drive through, thanks to the necessity to drive slower and more prudently. That is, a nice slice of through traffic would be encouraged to find faster routes (arrow **C5**). From this perspective, traffic engineers must provide attractive alternative routes in the adjacent road network.

In addition, pedestrians have to be attracted within the area by creating a sense of place, for which public spaces are designed. This is also called "furnishing of public space" and belongs to the discipline of urban design. It includes the creating of placing to rest (as seats), to eat (as vending carts and bars), children's play, to admire (water features), to interact with (activities); moreover, lighting and waste receptacles are essential to increase human comfort. The list of possible attractors is long. A high number of pedestrians in relation to vehicles is fundamental to increase the perception of the area as a public space rather than a traffic corridor. Moreover, it has an influence on driver behavior: "The more pedestrians using the street, the more slowly vehicles tend to travel" [80]. Further, "Drivers are more likely to behave courteously to pedestrians where they appear to be dominant user group" (arrow **C6**).

2.3 Performance evaluation

The debate about shared spaces is commonly based on the rough question whether they effectively "work". This happens to all "unconventional" theories in a wide range of fields, with advocates on one side and opponents on the other. In this case, the dispute is also amplified by confusion about the term "shared space", which may refer to different things depending on the context. Moreover, the multidisciplinary of this topic makes it difficult to establish overall criteria to evaluate the success or the failure.

This dissertation focuses on the traffic perspective. That means a shared space is assumed to be successful if it succeeds in the improvement of pedestrian condition and traffic safety, i.e., the goals of shared space design. In light of this, an analysis on the state of the art over shared space evaluation is performed here relatively to the aforementioned aspects. For the sake of clarity, the classification of different evaluation methods, as well as the performance indicators, reflects the definition of shared space objectives carried out in Sec. 2.2.2

Vehicle dominance

A key element for the success of shared spaces is represented by the reduction of vehicle dominance. As indicated in Sec. 2.2, this can be represented by three aspects, i.e., driving speed, traffic volumes and yielding behavior.

Karndacharuk et al. [49], as part of a safety analysis in a shared zone in Auckland, New Zealand, evaluated the three aspects all together. The reduction in traffic volumes was investigated by counting vehicle volumes for a period of one week, before and after the site transformation. Comparison of the daily profile of traffic volumes has highlighted, in that very case, how the implementation of a shared space has effectively diverted traffic away, for an entire day approximately by 40%. Speed reduction was investigated by analyzing the 24-h operative speeds, averaged over a one-week period. The daily speed profile in fact can reveal in which moment of the day the transformation has effectively achieved the objective of speed reduction. The authors found that in the off-peak hour speed reduction did not occur just because of the lack of pedestrian movement and activities. Moreover, the distribution of vehicular speed, before and after the shared space upgrade, is indicative of the driver behavioral change. In the case under investigation, the authors found that both mean and variance have decreased. Finally, the tendency of motorists to yield was analyzed. It was discovered that drivers tend to give way much more often by shared space design, i.e. from only 10% of pre-implementation to approximately 60% of post-implementation, all day long.

Schönauer [72] also analyzed vehicle speed distribution before and after the transformation of Sonnenfeldplatz in Graz, Austria. Despite speed being not found to significantly decrease, it was discovered that variance was narrower, indicating a more constant speed of motorists and less stop and go behavior. In this sense, the transformation has homogenized traffic and allowed a more regular traffic flow. The authors also used a speed map to investigate the spatial distribution of speed. This was performed by dividing the space in a cell grid of size 1m x 1m and computing the average value. In the new street configuration, peaks of driving speed were found to disappear.

Space sharing

Space sharing regards how much and how well road users interact with each other. In the previous literature, interaction was analyzed by investigating the dynamic of conflict situations between motorized and vulnerable road users. The aim was to discover if, as hoped, interaction has increased and if the severity of conflict has decreased.

Kaparias et al. [45] developed a method for analyzing vehicle-pedestrian traffic conflicts in shared spaces called pedestrian-vehicle conflict analysis (PVCA). The method allows one to identify a traffic event and to estimate the grade of the conflict in the range from 1 (slight) to 4 (serious). The grade is based on four different aspects of a conflict, i.e. Time To Collision (TTC), severity and complexity of the evasive action, and distance to collision. The numerousness of traffic conflicts and the respective grade were then compared before and after site transformation in order to discover changes in the vehicle-pedestrian interaction dynamic. The method, which was developed within a safety study on Exhibition Road in London, was also used by Karndacharuk et al. [49] within the previously mentioned safety study of shared spaces in Auckland, New Zealand.

Kaparias et al. [43] analyzed the interaction of pedestrian and vehicles in shared streets via the employment of a new behavioral analysis technique. The basis of the analysis was video observation, whereby events (i.e., traffic conflicts) were recorded and evaluated according to a number of criteria, with respect to their nature and severity. Criteria included the change in walking (or driving pace) and change in direction and acceleration. The method was applied to Exhibition Road in London and allowed to state that the site transformation has increased pedestrian confidence in interaction with vehicles but did not seem to have changed the behavior of motorists.

Within a study on the effectiveness of the site transformation of the above-mentioned Sonnenfeldplatz in Graz, Austria, Schönauer [72] performed a safety analysis by a new indicator. The idea was to consider each conflicting pair, consisting of a vulnerable road user and a vehicle, and to compute the quotient of the squared relative speed and the distance between the object (with side constraints as the maximum distance of 5 m and a time difference of 3 s). By plotting this value over the two-dimensional space, a straightforward spatial analysis of the most dangerous areas can be performed.

Pedestrian space usage reveals the relation among pedestrians, motorists, and the sourrounding environment and is an indicator of space sharing. Karndacharuk et al. [48] has developed different key performance indicators for pedestrians to investigate different features of pedestrian space usage. To inspect the function of place, the pedestrian occupancy ratio was used to measure the percentage of user dwellings in the area, with respect to the total number of pedestrians. Moreover, the user dwell time was used to capture the mean time effectively spent by pedestrians in the areas. As indicated by the authors, both are a possible measure to indicate that the zone can serve "as an origin/destination rather that a through route". With respect to function of movement, pedestrian density and trajectories were analyzed. This can reveal if the whole space is effectively used and if pedestrians prefer to avoid the interaction in the carriageway area by crossing perpendicularly (i.e., to minimize the interactions with motorists) Schönauer [72] has investigated the space usage of different types of road users. The analysis was aimed at comparing the trajectories before and after the site transformation to discern if behavioral changes have occurred. The analysis showed that by shared space design pedestrians tend to choose shorter paths, closer to the square center. Moreover, a higher variety in path alternatives was found, which indicated higher freedom of movement.

2.4 Shared space modeling

In recent years, traffic simulation models have become increasingly popular and are widely used in the evaluation of transportation systems. The benefit of these tools is to test road designs, traffic controls, and management measures in a dynamic way and to obtain a visual explanation of results. These instruments are useful for practitioners and decision-makers because they allow them to “make informed decisions” [25] as a result of precise performance indicators. The advantage is to evaluate potential improvements of the existing transportation system, called “scenarios”, and to make comparisons.

Based on the required level of detail, analysts can use different approaches, e.g., macro-, meso-, and micro-simulation. The latter, in particular, is suitable for complex transportation systems because it operates at an individual unit level. In this way, these instruments can capture the behavior of individual road users and the mechanisms of mutual interaction, which would not be represented by less-detailed models. The employment of microsimulation tools in traffic engineering varies from the field of traffic operation (e.g., computation of the optimal signal timing), roadway design (e.g., capacity studies) to transportation planning issues (e.g., to compare different investment scenarios).

When dealing with shared spaces, microsimulation appears to be challenging especially on three main points. The first is related to the presence of different types of road users, which have distinct mechanical characteristics, operative speeds and dynamics of motion. As a consequence, different motion models must be developed for every type of road user, preferably in a unified theory and modeling structure. The second is related to the pattern of movement. Contrarily to classical microsimulation models, the behavior cannot be assumed as lane-based. Indeed, the possibility for pedestrians to move freely around the street requires a 2D motion model (i.e., two degrees of freedom instead of one). The third regards the mechanism of interaction, which is not the consequence of clearly defined rules, as traffic rules, but the result of space negotiation. Each road user adjusts his/her trajectory as a social mechanism to avoid collisions as well as to keep a respectable distance from others. In this process, the role of existing traffic rules is unclear and can justify only a part of the observed behavior, though not entirely. The other motion dynamics have to be properly investigated and modeled.

2.4.1 Modeling approach

In light of the above-mentioned aspects of road users' motion in shared spaces, two different microsimulation approaches can be reasonably used, which are cell-based or continuum models.

The first consist of a system of agents that behaves and interacts according to a set of predefined rules, which could be both environment- or agent-specific. The space is discretized into an array of regular cells, whose size is decided by the modeler. At every time step, each agent moves to an adjacent cell depending on the laws of the system. In transportation science the cellular automata (CA), which is basically a fixed-grid cell-based model, has found many applications both for macroscopic and microscopic simulation.

The second ones are based on a set of partial differential equations, which relate the speed variation of the agent, defined as a bi-dimensional vector, to a set of forces acting on the agent. For the aim of simulation, partial differential equations are discretized in time, so that the new position of the agent in the next time step can be determined. Note that these equations are the equivalent of the rules of cell-based models and represent the influence of the environment or other agents. After the introduction of force-based models [33], a new formulation was introduced [36] under the name of the social force model (*SFM*). The model was developed for pedestrian dynamic studies and in analogy with the gas-kinetic theory. It is currently the most used approach (also found in commercial traffic simulation software) for pedestrian modeling.

With the purpose of modeling the movement of road users in shared spaces, the question about the most suitable approach arises. Cell-based models have the disadvantage of low level of detail as a result of space discretization; thus, single cells can be occupied only by one agent at time. On the contrary, a force-based model can more accurately reproduce the movement of users since the space is continuous. Nevertheless, space discretization makes the model simple and straightforward. Moreover, the set of predefined rules can be rapidly executed in sequence. Instead, a force-based model implies a double integration at every time step and solving such a system of equations using numerical methods is computationally expensive.

In previous research, shared space modeling has been mainly dealt with by force-based models. This approach is also chosen in this work for the reasons listed below.

Accuracy In this dissertation, the focus is on a microscopical level of an agent‘s dynamics. That means we are interested in studying the spatial and speed behavior of road users. With this purpose, the spatial discretization of cell-based models would represent a strong limitation. By a continuum model, direction and speed variation can be modeled with high precision and without discretization.

Computational time Minimizing computational time is not considered an objective. In other words, we do not ask the algorithm to be efficient. In the case of high computational efforts, the simulation area and run times will be accordingly restricted in order to obtain results within a reasonable time.

Heterogeneity The cell-based structure does not mix well with road users' heterogeneity, especially with different sizes and speeds. Despite extensions and modifications to basic cell-based models accounting for this, it is more straightforward to employ a force-based approach and to simply define different agents. Desired speed, for example, is already included in the formulation of partial differential equations and is easy to be defined for every agent.

Density Shared space streets are high density-pedestrian environments. The simulation of many road users within a small area would imply, via cell-based models, a low size of cells and a high number of rules, which would weight down the model. Contrarily, a force-based model has been specifically developed to represent a high density-pedestrian environment, e.g., movement or evacuation of crowds.

2.4.2 Previous research

Force-based model have been employed in previous research for the development of microsimulation models for shared spaces. The common basis in these works is the social force model (*SFM*) in the formulation of Helbing and Molnar [36] or later formulations [37, 35, 34, 41]. However, shared space modeling poses complex challenges which were not addressed in the classical *SFM*. First, the heterogeneity of road users - not only pedestrians but motorists and cyclists as well. Second, the characteristics of movement patterns, i.e., motion dynamics cannot be assumed as lane-based, as they are bi-dimensional. Third, the type of interaction rules is based on space negotiation and not on compliance with clear traffic rules.

In order to deal with these modeling challenges, previous research has proposed extensions and integrations of the classical *SFM*. The main focus was on three points, which were needed to overcome the above-mentioned limitations of *SFM*:

- the formulation *SFM* approaches for vehicle-based users;
- the development of algorithms for 2D path finding;

- the implementation of models to address interaction among users.

Moreover, the development of a microsimulation model is finalized to the construction of a tool, which has first to be calibrated and validated and then successively implemented in a simulation instrument to allow the systematic reproduction of new scenarios.

The review of the state of art on shared space modeling has been organized in the following subsections according to the mentioned issues.

Modeling vehicle-based users

The presence of mixed traffic in shared space requires us to extend the *SFM* to non-pedestrian users. However, the movement of motorists and cyclists follows entirely different principles and rules, which are precisely related to the presence of two- or four-wheel vehicles. This is not only a matter of different operative speeds and acceleration rates, but especially of degrees of freedom by directional change, which restrict the possibility of lateral movement. Under these circumstances, the classical *SFM* would present unrealistic results, since it would allow sudden directional changes that are inconsistent with vehicle mechanical constraints.

Anvari et al. [7] introduced an *SFM* formulation for cars, in which the force terms are adapted to consider the influence of pedestrians and other cars. The repulsive forces include a *socio-psychological* term, to keep a certain distance from nearby users, and a *deceleration* term, to cover the car-following behavior. Moreover, to include the restriction of lateral movement, a relation between steering angle and moving velocity was established.

Schönauer [72] also proposed an approach for extending the *SFM* to four-wheel vehicles. This is based on a mechanical dynamic model which determines the successive position of the vehicle based on the initial position and steering angle. Within the model, longitudinal and lateral forces are considered separately, since the first one influences the acceleration of the vehicle, the second one the directional change. The model is capable of determining the final trajectory of the vehicle based on fixed obstacles and moving road users, thus simulating turning behavior as well as car-following features.

Modeling path finding

Shared spaces allocate high degrees of freedom to road users. Contrarily to traffic facilities in which road users follow clearly defined paths, as road lanes for cars or footpaths for pedestrians, in shared spaces road users have an open space at their disposal. The environment may present fixed obstacles of various kinds as well as a delimited space in which vehicles are expected, typically referred to as *carriageway area*. This makes the problem of path finding complex and requires the development of a specific algorithm.

Anvari et al. [7, 6] developed a distance potential field by the flood fill algorithm. The floor area is divided into separate cells, in which each is assigned a distance value. Successively, a global shortest-path strategy was developed to obtain the desired path of each road user in a given position via intermediate destinations.

Schönauer [72] developed a "tactical model" to find an individual path given an origin and a destination. The model is based on a potential field that keeps the user on his/her track, avoids obstacles and maintains a distance to borders. This "guiding field" is then used to calculate a social force. which pulls the agent to the position where the value of attractiveness is maximum, e.g., the middle of the lane for cars.

Modeling interaction

The mechanisms of space negotiation among road users represent the main challenge for shared space modeling. They consist of performing behavioral changes to avoid collisions as well as to keep a safe distance from others. Two main aspects have to be considered. First, it has to be defined *when* (in which condition) a behavioral change is needed. Second, it must be determined *how* (in which manner) a behavioral change is performed.

The first issue was addressed in previous research by developing conflict detection algorithms to identify if road users would collide or would find themselves too close with each other. Anvari et al. [5, 6] developed a model that predicts potential conflicts between road users. The model is based on geometrical considerations and is able to predict intersecting trajectories by comparing future relative distances between road users. Schönauer [72] created a conflict-detection model by computing at each time step the expected path of all road users. Successively, trajectories are compared to find pairs conflicting in time and space.

The second issue concerns the modeling of reaction strategies. Anvari et al. [5] classified them into speed change, steering change, or a combination of both. Their intensity is computed by minimizing a cost function, which describes the velocity change needed to avoid conflicts. Successively, a conflict avoidance force is calculated and added to the sum of forces. Schönauer [72] developed a method for conflict handling based on game theory, which states which type of reaction should be possibly taken. Once the reaction is selected, a game theoretic force component is added to the social force model.

Model calibration

After formulating modeling approaches for free-flow and interaction, the major concern is to calibrate the model to better fit the real behavior of road users. Previous studies have proposed calibration methods that compare simulated and real-world trajectories of road users, with the aim to minimize the deviation between them. That is to say, the behavior of road users is captured in space and time by video-tracking methods and successively compared with the estimated one, which comes from the simulation.

Rudloff et al. [69] presented a calibration method for the developed of shared space models based on real-world data from Gleinstätten and Graz, in Austria. Among the video material, two type of scenes were manually cut: The first one consisted of single vehicles driving through the intersection and were used to calibrate the free-flow behavior. The second one included conflict situations between pedestrians and motorists and were used for the calibration of the *tactical game*, which models the strategies for conflict avoidance.

Anvari et al. [4] calibrated the developed shared space model using real data from Exhibition Road in London. Trajectories were automatically extracted by an external software and used as reference for the calibration, which was aimed at minimizing deviations between real and simulated pedestrian and car trajectories. In more detail, single scenes were reproduced by setting the same initial data, as initial position and speed. Many parameter combinations were tested and the one with the minimum value of the fitness function, based on the deviation between real and simulated trajectory, was chosen. Finally, the model was validated by comparing speed and acceleration distributions and trajectories of real-world data to the simulation results.

Model implementation

The development of a shared space model is finalized with the implementation in the microsimulation tool, by which different space configurations and traffic volumes can be tested. Anvari et al. [5] implemented the mathematical model in a simulation platform based on Visual C#. Rudloff et al [69] implemented the model in the PTV VISSIM simulation program, which also has capabilities to render objects in three dimensions.

2.4.3 The Social Force Model

The microsimulation approach developed in this work is based on the social force model (*SFM*), which was formulated in 1994 by Dirk Helbing and Peter Molnar [36] and gained the immediate attention from the scientific world for its innovative and original approach.

Over the years, the *SFM* has established itself as the most-used approach for pedestrian microsimulation and is currently the most widely used model in traffic microsimulation software.

As specified by the authors, Lewin [51] suggested that behavioral changes are governed by *social fields* or *social forces*. Helbing and Molnar then applied this concept to the pedestrian dynamic according to the principle of stimulus-reaction, i.e., the stimulus is represented by the environment around the pedestrian and represents a *motivation to act*, and the reaction is the behavioral change, which is the direct consequence of the stimulus. The intuition of the authors was to integrate this principle into the Newton's second equation of motion, which states the equality of *stimulus* and *reaction*, indeed. Starting from the original formulation in 1995, the model has been modified and improved over the years in order to reproduce the movement more realistically. In this work, the formulation of Johansson et al. [41] is used and is recalled here in general terms.

The basic principle of *SFM* is that a pedestrian i adapts at time t the actual velocity $\vec{v_i}$ according to an acceleration force $\vec{f_i}(t)$ [Eq. (2.1)]:

$$\frac{d\vec{v}_i(t)}{dt} = \vec{f_i}(t) \tag{2.1}$$

where the velocity v_i corresponds to the temporal change of location $d\vec{x}_i(t)/dt$. The acceleration force $\vec{f_i}(t)$ is the stimulus for behavioral change and includes three different contributions [Eq. (2.2)]:

$$\vec{f_i}(t) = \vec{f_i}^0(t) + \sum_{j,j\neq i} \vec{f_{ij}}(t) + \sum_b \vec{f_{ib}}(t) \tag{2.2}$$

The first term is called the *driving term* and represents the motivation to move towards a certain destination. This contribution is assumed to depend on the given direction, $\vec{e_i}^0(t)$ and the desired speed, $v_i^0(t)$ of the pedestrian and is scaled by a certain relaxation time τ [Eq. (2.3)]:

$$\vec{f_i}^0(t) = \frac{v_i^0 \cdot \vec{e_i}^0(t) - \vec{v}_i(t)}{\tau} \tag{2.3}$$

The second and third term defines the repulsive effects, respectively, from other users j and from obstacles b.

In the *SFM*, the 2D projection of the human body is modeled by means of ellipses with velocity-dependent semi-axes. Moreover, road users have a range of visibility that consists on a circle with radius r_i and angle ϕ_i. Behavior changes are performed only if other users, or obstacles, find themselves within this perception area. The intensity of the interaction with other road users is governed by the value of the relative distance $b_{ij}(t)$, which is defined as [Eq. (2.4)]:

$$b_{ij}(t) = \|\vec{x}_{ij}(t)\| - R_{ij}(t) - R_{ji}(t) \tag{2.4}$$

where $\|\vec{x}_{ij}(t)\|$ is the distance between body centers, and $R_{ij}(t)$ (or $R_{ij}(t)$) is the dynamic radius of the ellipse in the mutual direction, $\vec{e}_{ij}(t)$. In light of this, the repulsive force is defined as an exponential function and is controlled by the intensity s_{ij} and the range of influence r_{ij} [Eq. (2.5)].:

$$\vec{f}_{ij}(t) = s_{ij} \cdot \exp\left(- \frac{b_{ij}(t)}{\omega_{ij}(t)\; r_{ij}} \right) \cdot \vec{e}_{ij}(t) \tag{2.5}$$

The weight factor $\omega_{ij}(t)$ takes account of the anisotropic behavior. That means other pedestrians j in the direction of motion have a greater influence in comparison with those on the side. In regard to the formulation of $\omega_{ij}(t)$, please refer to Schiermeyer et al. [70]. Please note that the repulsive force toward obstacles j has the same formulation.

3 Data collection

Survey methodology and consequent evaluation are outlined in this section. A shared space in the district of Bergedorf, in Hamburg (D), was chosen as the case study and used for the development of this research. First, the analysis of crossing movement was used to develop and calibrate a new Measure Of Effectiveness (MOEs) for pedestrians which considers comfort (covered in Chap. 4). Second, the investigation of common tendencies and behavioral patterns in road users' interaction served to develop a new modeling approach for microsimulation (covered in Chap. 5). Third, the acquisition of trajectory data allowed the calibration of the developed model (covered in Chap. 6).

This chapter includes the definition of criteria for the selection of a suitable location (Sec. 3.1), the description of the chosen site (Sec. 3.2), the data survey and the process of data acquisition (Sec. 3.3), and finally a preliminary analysis of obtained data (Sec. 3.4).

3.1 Site-selection criteria

In this work, a single case study was examined. While considering many case studies would have helped in developing more comprehensive, holistic approaches, both for performance evaluation and microsimulation, this was not possible for the following reason.

Besides being a relatively recent design technique, which already limits the availability of case studies at the present time, shared space design is not standardized and is context-sensitive [45]. This means, that shared spaces may differ one to another depending on local context and design solutions, which vary from the width of the carriageway's area, materials used as the surface, elements on the roadside, built environment, road regulations and so forth. As a consequence, road users' behaviors may differ significantly from one shared space to another (as noted in Chap. 2, there is a strong relation between street design and user behavior). For this reason, given that every element may potentially affect the dynamics of motion and interaction, a high number of cases should be examined to properly discover the influence of single elements.

However, limited resources were available for this work. Among them, the main technical limitation was the lack of a software to automatically track a road user's trajectory, which would have quickened the data-acquisition process. Instead, manual tracking could only cover limited time intervals within reasonable efforts (see Sec. 3.3). In light of this, considering many case studies would have been senseless, because the process of data acquisition would have result in poor databases, despite large efforts.

For this reason, it was decided to focus on a single case study, which had to be as standard as possible. The following requirements were formulated to choose the proper site.

High traffic volumes Generally, there are no particular concerns about traffic quality and safety when traffic volumes are low. Instead, it is interesting to discover how traffic performances vary when traffic demand increases. This issue can be properly inspected only if the site under analysis accommodates for high inflows of vehicles, at least in the peak-hour.

Road section As stated in the thesis objective of this thesis, this study will focus on shared streets rather than shared intersections. The shared space design principle has been implemented in a wide variety of configurations, e.g., streets, T-junctions, X-junction, or squares. Among them, the simplest case to be investigated (as well as the most widely used) consists of stretches of roads, in which vehicular traffic flows longitudinally and pedestrians cross from one side to the other of the roadway. These configurations are convenient for pedestrians since vehicular traffic is spatially constrained, as it drives along the main axis and does not deviate from it, thus making crossing easier to perform. This case is mentioned in the German guidance note [9] as "Lineare Querungsbedarf" (lit. linear crossing need). In this case, shared streets can also be seen as "alternative" crossing facilities. In fact, instead of "puntual" facilities, which allow the cross at a given location, pedestrians can use any part of the road section.

Negligible number of cyclists As investigated in the guidelines in Chap. 2, the success of shared spaces is mostly related to two factors: the improvement of pedestrian movement and comfort, on one hand, and the reduction of vehicle dominance, on the other hand. Therefore,this study concentrates on these two types of road users (i.e., pedestrians and motorized vehicles), which plays a major role in achieving the study's goals. Other road users, as cyclists, are not considered in this work. For this reason, the case study should possibly accommodate a negligible number of cyclists, which would otherwise interfere in the interaction dynamic between pedestrians and vehicles and in the traffic performances.

De-cluttered environment To keep shared spaces as standard as possible, the street environment should possibly be minimal. In this way, the effect of any elements of street furniture (e.g., seats, vegetation, poles) is minimized; consequently, it would not consistently affect a road user's behavior. This concept is usually referred to as "de-cluttering" and consists of street clutter reduction.

German context Given the context of this dissertation, it was chosen to focus on a case study in Germany. The aim is to represent the state-of-the-art of shared spaces in Germany, including the design features, existing road regulations, and road users' behaviors.

In the light of these requirements, a shared street in the district of Bergedorf in Hamburg (D) was selected as the case study of this research work.

3.2 Site description

Bergedorf is a quarter of the namesake district of the Free and Hanseatic City of Hamburg, in Germany. It is located in the southeast side of the city, approximately 20 km away from the city center. It is more than 10 km^2 wide and has a population of 35,000 inhabitants; further, it is one of the most populated quarters of Hamburg. It is connected with the city center by the Federal Highway B5, Bergedorfer Straße (see Fig. 3.1, left), which, in the proximity of Bergedorf, is two lanes per direction and has an average daily traffic volume of 40,000 vehicles. Moreover, the center of Bergedorf is connected by railway (i.e., regional and suburban trains) which stops at the Hamburg-Bergedorf station. The quarter center, indicated by concentric circles, includes a big garden (Schloßgarten) and a historical pedestrian area, which is surrounded by a river.

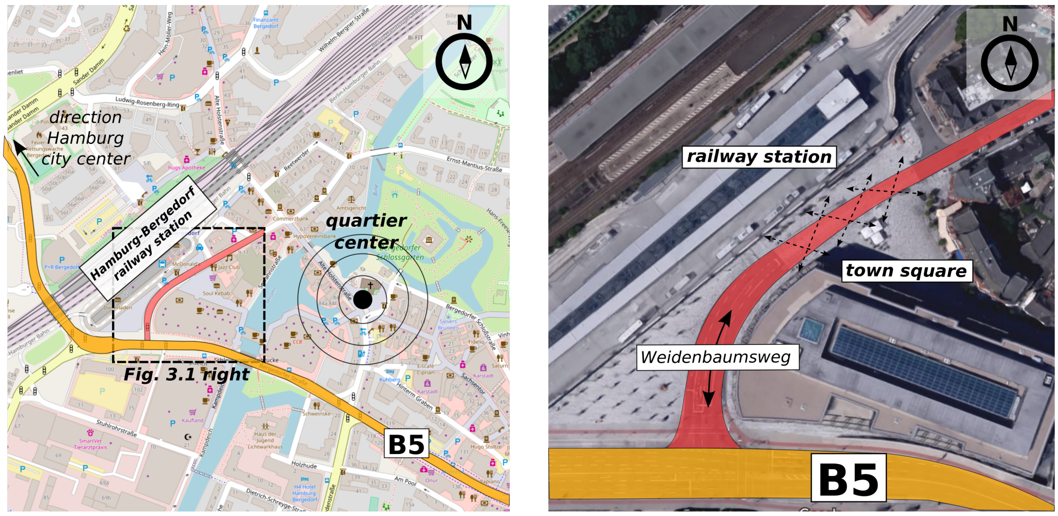


Fig. 3.1. Geographical context of the case study

From the perspective of urban road planning, the Weidenbaumsweg corridor is located in a strategical position (Fig. 3.1, right). It surrounds the quartier center from the west side and connects traffic from Federal Highway B5 and the northern internal ring of Bergedorf.

Moreover, it crosses the pedestrian axis from the railway station to the town square. This means that high pedestrian volumes are expected to cross the Weidenbaumsweg (see the dotted lines).

The stretch of Weidenbaumsweg in front of the railway station is designed according to the shared space principle. In a 63-meters-long road section, there is no remarkable level difference (only a 2-cm-high curbstone) between the carriageway's area (here referred to as *circulation zone*) and the pedestrian zone (here referred to as *comfort zone*) (Fig. 3.2 left). The shared street is surrounded by the railway station to the north and by a public square with retail stores and a shopping mall to the south. The surface within the area is paved by a white-gray pattern, whose plot differs depending on the type of zone (see Fig. 3.2 right). Moreover, the separation between circulation and comfort is indicated by two paved stripes, white and black.

Fig. 3.2. Site location: Aerial view and zone delimitation (left), photo from the bus station in point P (right).

The current layout and appearance are the result of street redevelopment, which included the construction of the new railway station, the shopping mall, and the town square. In order to promote pedestrian movement between these areas and to facilitate crossing of the Weidenbaumsweg, the administration has adopted the shared space design principle. The work time has covered the period 2008-2012, meaning that the shared street was four-years-old at the moment of investigation and data survey. This indicates that the inhabitants have had enough time to get acquainted with the features of the new shared street and are well informed - and experienced - about how to behave on the street.

By accessing the circulation zone within the shared space, vehicles are notified to drive up to 20 km/h by the indication of a *Verkehrsberuhigter Geschäftsbereich* (traffic-calmed shopping area). This type of regulation in Germany (commonly referred to as *Tempo-20-Zone*) implies a speed limit for motorists but still allows them the right of way over crossing pedestrians. Nevertheless, it was observed that vehicles are used to yield to pedestrians quite often, by decelerating and in some cases up to stopping. The reason is that street design is self-explanatory and makes drivers more attentive, as well as more available to accord priority.

In other words, space negotiation effectively takes place despite posted traffic rules, which are not strictly observed.

3.3 Data survey and acquisition

The area was recorded with two video cameras of 640 x 480 pixel resolution and 30 frames per second, which were mounted at an elevation of about 7 meters. The video survey was conducted on Saturday, April 2, 2016, from 1:30 p.m. to 4:30 p.m. This temporal interval (of the day, week, year) was chosen for the high amount of traffic expected. Moreover, high presence of pedestrians was facilitated by the sunny weather. Camera were placed at opposite borders of the *circulation zone* (see points A and B of Fig. 3.2, left), across from each other (Fig.3.3). A view from video cameras in the same instant is provided in Fig.3.4 (as a reference, note the white car).

Fig. 3.3. Camera positions and range of view

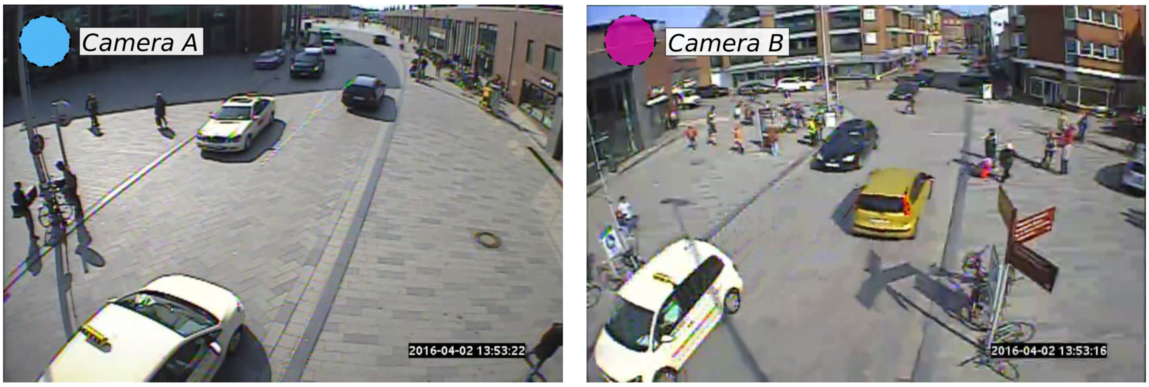


Fig. 3.4. View from cameras: camera A, direction southwest (left), camera B, direction northeast (right)

The whole video material was used to detect common behavioral tendencies of road users, which is useful for the development of a modeling approach. Instead, for part of the model calibration and performance evaluation, a detailed analysis of movements was performed. The aim was to determine the behavior of road users in space and time by capturing their position at fixed time steps. With this purpose, a half-hour period between 1:50 and 2:20 p.m. was selected. In this period, the pedestrian volume was found to be the highest among all video material. Therefore, this part of the video was cut and submitted to a detailed procedure for trajectory acquisition, which is listed and commented on below.

Defishing A fish-eye lens allows a camera to create a wide panoramic view, but produces strong visual distortion. With the purpose of trajectories' tracking, lens distortion was removed, so that the resulting image would have straight lines of perspectives. This operation was carried out by the software Virtual Dub [8] and results, naturally, in the loss of image corners. This operation is commonly referred to as *lens adjustment*.

Tracking The position of road users was tracked at discrete time steps of 0.5 seconds. For pedestrians, the point tracked consisted of the projection of the body barycenter on the ground. For vehicles, the tracked point consisted of the projection of the observable extreme of the car (front or rear) on the ground. This operation was carried out manually by help of the software Tracker [24][1]. However, mild inaccuracies may have occurred through this stage for two main reasons. The first is related to technical limitations and consist of low video resolution (640 x 480 pixel) as well as screen size, where the tracking was manually carried out (around 23 inches). The second is related to the difficulty of truly projecting an object, i.e., the body barycenter or the extreme of the car, on the ground. This operation is supposed to be less inaccurate for pedestrians because parts of the body (i.e., the feet) are already laying on the ground. In this case, the tracked point is guessed along the direct line between feet and by considering the chest position. However, for vehicles, higher errors could be committed because the front (or the rear) of the car does not lie on the ground. In this case, given also the misleading shadow of the vehicle, the tracking is less reliable. For all these reasons, the level of inaccuracy was surmised to be at maximum 25 cm for pedestrians and 40 cm for vehicles.

Transformation In order to have usable data, the tracked points were transformed from the coordinate system of the camera (3D real world) to a 2D image space. The operation is called *projective transformation*, or *homography*, and includes the computation of a linear transformation matrix which relates four points, detected both in the real world and in the image space. In this way, all tracked points coming from both cameras were imported in the same 2D coordinate system, which covers the whole area.

[1]The time effort for the analyst to perform this operation consisted approximately in 30 minutes of time for every minute of video footage. Considering the duration of the selected interval (30 min) and the number of cameras (2), this operation lasted around 30 hours.

Adjustment The tracked points of vehicles corresponded sometimes to the front of the vehicle, sometimes to the rear. To shift the position to the barycenter, the tracked points were moved along the symmetrical axis of the vehicle for two meters (assumed as an average half-length).

Joining The travel of road users who were detected by different cameras was reconstructed. If at a given time step, a user was observed in both cameras, the average spatial point was saved. If not observed at all, the user's position was inferred by mathematical interpolation.

Smoothing Pedestrian speed profiles are typically not uniform and show cyclic fluctuations that are repeated continuously over time [78]. Each fluctuation corresponds to a step taken by a pedestrian. In order to obtain continuous and stable trajectory data for pedestrians, which are needed, for example, in the conflict analysis, tracked points were smoothed in X and Y over time by a smoothing spline with 4 degrees of freedom. This operation was also performed for vehicles to reduce inaccuracy in tracking.

As a result of this procedure, the trajectories of all vehicles and pedestrians within the selected half-hour were obtained. This constitutes the data set of available trajectories and is resumed in Tab. 3.1. The process has not involved bicycles, motorcycles, and vehicles which were parked on the side of the road. The reason is that their volume was negligible, and they were assumed not to consistently influence traffic flow.

Type of Users	Size	Distribution	Tracking Time [s]		
			Q(.25)	Q(.50)	Q(.75)
Vehicles	299	55-45 % [1]	17	21	27
Pedestrians	1114	51-49 % [2]	9.5	12	15

[1] distribution between driving direction ([lane 1: south-west to north-east] - [lane 2: opposite direction])
[2] distribution between crossing direction ([south-east to north-west] - [opposite direction])

Tab. 3.1. Characteristics of the data set of trajectories after data acquisition.

3.4 Preliminary analysis

To obtain an overview about road users' behavior in the shared space, a preliminary analysis on the trajectory data set was performed and relevant results and pictures are provided.

First, insight into collected traffic volumes was carried out. Flow rate of a vehicle is around 600 veh/h, which corresponds to approximately 300 veh/h on each lane. Moreover, pedestrian flow rate is about 2,200 ped/h within an extension of about 60 meters (around six pedestrians per minute are crossing every 10 meters). The ratio between them is around four pedestrians for each vehicle. Analysis of the presence of road users shows that, within the shared area (which includes the 63-meters-long circulation zone and 5-meters-wide strips on the roadside) around eight pedestrians are present on average at every time step, against approximately four vehicles.

As explained in Sec. 2.2.2, the distribution of trajectory reveals the intensity of space sharing. To provide meaningful visual information, trajectories of vehicles and pedestrians were superimposed onto a black and white map in which comfort and circulation zone are marked. The results are shown in Fig. 3.5.

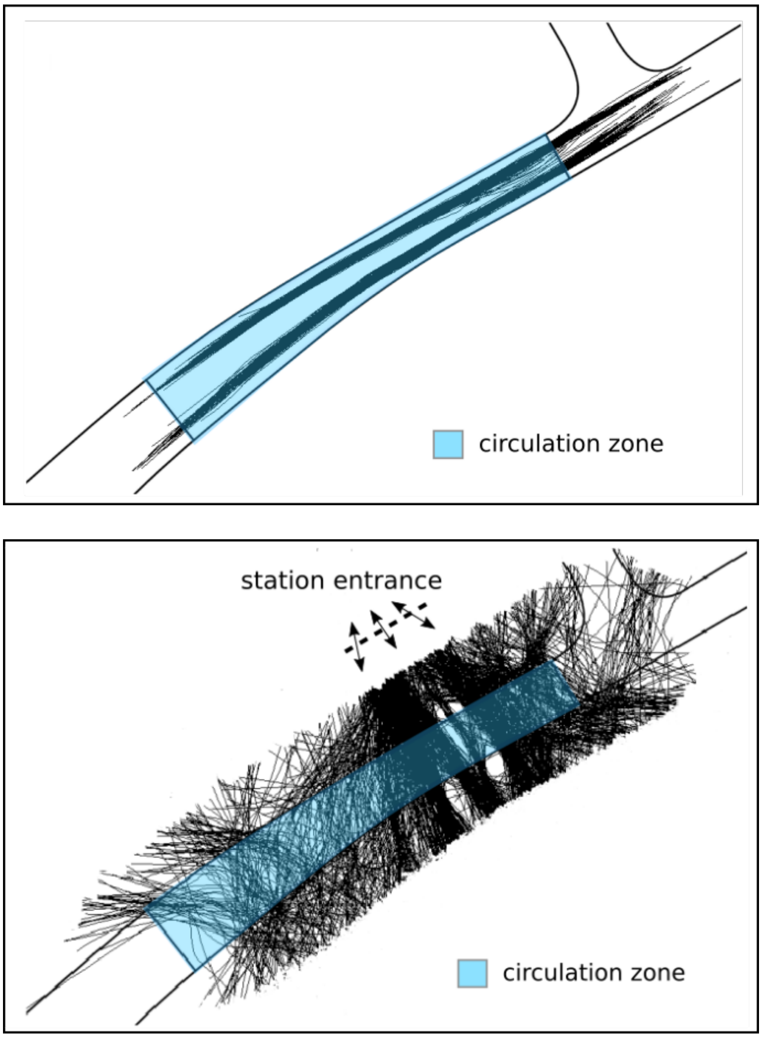


Fig. 3.5. Trajectories of all road users within the 30-min investigation period: vehicles (above) and pedestrians (below)

Vehicle trajectories appear to be gathered along the middle of each lane. Only a small deviation can be localized in the northeast, which is due to the temporary presence of parked vehicles. Except for short-term parking vehicles on the roadside, motorists are moving within the circulation zone, as expected. This confirms that, when a conflict with a pedestrian occurs, drivers tend to operate only speed modification (e.g., deceleration) without changing travel direction.

On the other hand, pedestrians make use of the whole road reserve and cross at different locations and in different directions. The figure is self-explanatory the high level of space usage. Moreover, crossing trajectories appear to be perpendicular to the road axes in proximity of the railway station; at transition areas, they are more tilted. Regarding the last point, it is noted that tilted trajectories denote high path directness (low deviation to desire lines), which translates in low travel times and high freedom of movement.

Besides the spatial distribution of trajectories, which represent road users' effective behaviors, the distribution of desire lines shows the intensity of relations between origins and destination (see Sec. 2.2.2). It may reveal if the shared surface was designed in the correct position, if it should possibly be extended, or if could also be restricted. This can be performed by identifying 10-meter-wide O/D locations on both sides of the circulation zone (18 in total) and filling the respective matrix of hourly volumes. The O/D matrix is provided in Appendix B, while the representation of the intensity of each relation is depicted in Fig. 3.6. Please note that centroids of O/D zones are identified with the acronym N for "north" and S for "south". It can be noted that the main routes are between N5-N6 and S4-S5-S6, with covers around the 60% of traffic demand. The current subdivision of traffic demand among origin and destination areas is also employed later on for model calibration and simulation.

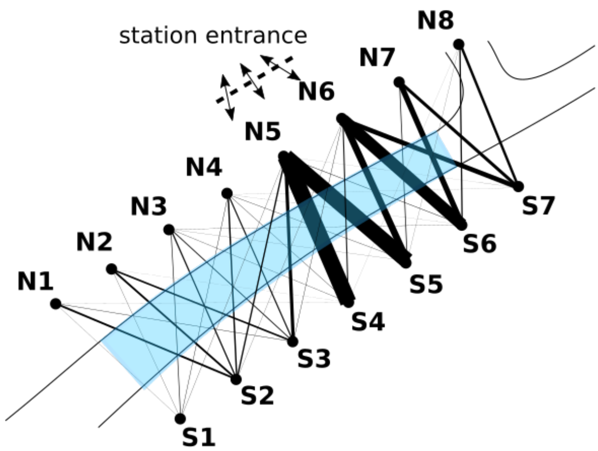


Fig. 3.6. Pedestrian desire lines

Speed behavior was inspected by calculating the instant speed at every time step for every road, independently from their position. This resulted in around 12,100 speed values, i.e., around 40 per vehicles on average. The histogram of instant speeds is plotted, both for vehicles and pedestrians, in Fig. 3.5. As also noted by Schönauer [72] for cars, the peak of speeds may be located around 0; as a consequence, many road users may sometimes arrest a vehicle to yield to pedestrians. Nevertheless, by considering only moving road users (i.e., by speeds equal to zero), the following results were obtained:

- the mode of speed distribution for vehicles is around 1.8 m/s (6.5 km/h). From this point, the frequency smoothly decreases. The 95th percentile is 6.3 m/s (22.5 km/h);
- considering the posted speed limit of the road (20 km/h), only around 8% of vehicle instant speed exceeds this value;
- the mode of speed distribution for pedestrians is around 1.2 m/s. Between 0.5 and 1.6 instant speed appears to be normally distributed with a slight left-skewness;
- considering the mean value of walking speed in unimpeded pedestrian flows of 1.34 as found by Buchmüller and Weidmann [20], only 23% of instant speed exceeds this value.

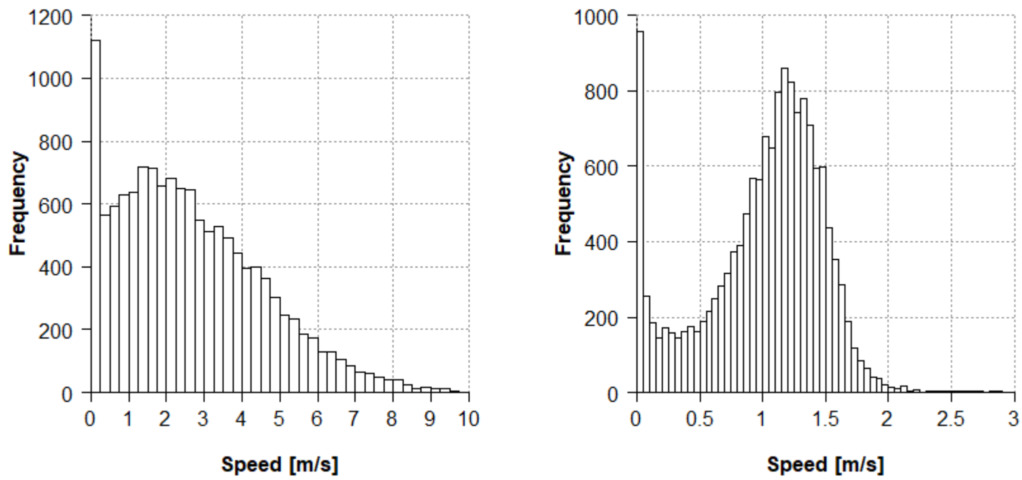


Fig. 3.7. Histogram of instant speed: vehicles (left), pedestrians (right)

While this investigation of instant speed was performed here to provide a first impression in road users' behavior, more in-depth analysis on pedestrian desired speed in the current case study is given in the next chapter.

4 Performance measures

Evaluation of a traffic system by microsimulation is performed by means of Measures of Effectiveness (*MOEs*). These indexes must be appropriate to the case study and must reflect the project objectives. As explained in Sec. 2.2, shared space design has two major goals. On the one hand, it has to improve conditions for pedestrians. As discussed in Sec. 2.2.1, by excluding the aspects related to the function of place and considering only that of movement, this goal corresponds to the increase of pedestrian traffic quality. On the other hand, the design has to improve traffic safety. Therefore, suitable *MOEs* for traffic quality and safety for shared spaces are discussed in this chapter.

Traffic quality is expressed by performance measures depending on the project's objectives, e.g., time delay, queue length, density, travel time or average mean speed. In order to provide more meaningful and straightforward information, these measures are usually converted into Level Of Service (*LOS*) via the help of specific tables on traffic guidelines, e.g., the *Highway Capacity Manual* (*HCM*) in the United States or the *Handbuch für die Bemessung von Straßenverkehrsanlagen* (*HBS*) in Germany. However, these handbooks do not provide recommendations for evaluating shared streets. For this reason, in Sec. 4.1, through analogy with unsignalized intersections, delay time was preliminary assumed as possible performance. Nevertheless, it is demonstrated via real-world examples that delay time itself is not solely capable of representing traffic quality for pedestrians. Therefore, this measure is revisited and integrated with other aspects of motion that are related to comfort. This new performance indicator is calibrated throughout a questionnaire, which was given to a group of respondents and successively tested in the current case study. Finally, as for classical traffic quality measures, a conversion in classes of *LOS* is provided.

Traffic safety refers to the number of fatalities and injuries that occur within a traffic facility. However, the unavailability of this information has encouraged over the years the use of surrogate safety measures (SSMs), which focus on traffic conflicts - in the real world or in the simulation - to draw conclusions about traffic safety. In Sec. 4.2, common SSMs are discussed, and some of them are selected for the case of shared streets. To provide valid examples, these measures are finally computed in a real-world situation.

4.1 Traffic Quality

Traffic quality is a qualitative measure of traffic flow. In contrast with quantitative measures, which only considers the characteristics of a traffic facility (as capacity), traffic quality measures express the relationship between the flow (traffic demand) and the facility itself (traffic supply). This measure is given by specific indicators called Measure Of Effectiveness (MOE), which focus on single aspects as time delay, or average speed, which are assumed to be representative of the quality of traffic. To generalize the measure of quality from the specific aspect considered, *MOEs* are converted in terms of Level Of Service (*LOS*), which ranges from level A to F.

The identification of the proper *MOEs* on a case-by-case basis is up to the modeler and must consider the type of system (or facility), the type of road user, and aim of the analysis. Dealing with interrupted flow for example, traffic engineers assume control delay time as a measure of quality. The reason is that traffic control devices must be efficient and minimize delays.

Instead, when dealing with sidewalks, pedestrian density is used as the reference *MOE*. This measure is assumed to influence traffic quality for two main reasons. First, high densities make the path tortuous, requiring deviations and decelerations, which make the trip longer. With this in mind, travel time increases, and the trip becomes less efficient. Second, by high densities, pedestrians would feel more constrained. In other words, the freedom of movement decreases. This aspect is not related to the efficiency of the trip, i.e., time spent, but is in regard to walking comfort and human perception.

Focusing on shared spaces, the matter about which *MOE* can truly represent traffic quality is disputable and controversial. Conventional measures such as average speed or delay time, indeed, capture the efficiency of traffic. Instead, shared spaces are aimed by definition to the improvement of pedestrian movement and comfort. This means that human perception and walking comfort must be included in the evaluation.

Starting from this fundamental consideration, in Sec. 4.1.1 the Handbuch für die Bemessung von Straßenverkehrsanlagen (*HBS*) [76] reveals which efficiency-related *MOE* would be the most suitable for shared streets, which was found to be the delay time. Sec. 4.1.2 shows, via help of real-world examples, that delay time is not able to solely capture the traffic quality for pedestrians. This confirms the idea that aspects of walking comfort must be integrated into the evaluation of traffic quality. Therefore, Sec. 4.1.3 investigates how delay time can possibly be extended and refined to include comfort aspects. This is carried out by asking a group of respondents to observe real-world situations and to evaluate the movement of specific pedestrians, in different traffic conditions and by a discrete scale. Based on the results of the questionnaire, a new indicator of traffic quality for pedestrians is formulated. This new *MOE*, which fits shared streets, is finally applied to the case study, and a *LOS* classification is proposed.

4.1.1 Delay time as conventional MOE

The Handbuch für die Bemessung von Straßenverkehrsanlagen (*HBS*) [76] and the Highway Capacity Manual (*HCM*) [17] do not propose any method for assessing the traffic quality of shared spaces. Given the lack of existing methods, the idea is to refer to similar cases, which are dealt with in the manuals. Two aspects were considered determinant. First, the feature of two traffic flows crossing each other: vehicles driving longitudinally and pedestrians walking perpendicularly. Second, the presence of priority rules - instead of control devices - to regulate traffic flow. By these aspects, intersections without traffic lights (S5.2.2 of the *HBS*) are used as reference to investigate conventional *MOEs*. The similarity between these cases is depicted in Fig. 4.1. On the left, the case of the T-junction is shown as in the *HBS*; on the right, a shared street is similarly sketched by representing priority rules and traffic relationships.

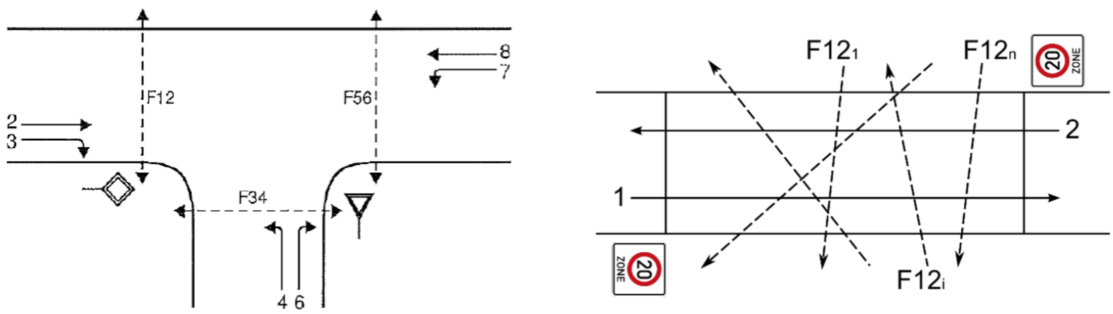


Fig. 4.1. Conflicting traffic flows: T-junction from HBS (left), shared street, proposed here (right)

In T-junctions, six vehicles (2, 3, 4, 6, 7, 8) and three pedestrian traffic relationships (F12, F34, F56) are represented respectively by solid and dashed lines. For each of them, the *HBS* recommends to compute delay time and to express it in terms of Level Of Service via a conversion table, which is shown in Tab. 4.1. Delay time is defined as the difference between the effective travel time needed and the time that would be required in free flow. It can be determined for a single vehicle or as an average for all vehicles over a given time period. According to this method, the delay experienced is *the* measure of traffic quality, because it is assumed that better quality is achieved when an intersection is crossed as quickly as possible.

In the shared street sketch (Fig.4.1 right), vehicular traffic drives according to Relations 1 and 2, while pedestrians crossing the carriageway's area are included in the Relation F12. Both flows are expected to be delayed; further, despite that vehicles have the right of way, the negotiation of spaces encouraged by road design may cause additional travel times.

LOS	Vehicles	Pedestrians
A	$\leq$10	$\leq$5
B	$\leq$20	$\leq$10
C	$\leq$30	$\leq$15
D	$\leq$45	$\leq$25
E	$>$45	$\leq$35
F	-	$>$35

Tab. 4.1. Benchmarks: mean delay time [s] for the Level of Service estimation according to HBS 2015 (S5 Urban streets, intersection without traffic light)

Following the T-junction approach of *HBS*, delay time can be similarly computed for traffic relations 1,2, and F12. Nevertheless, while the effective travel time is always available (from data survey or microsimulation), free-flow time has to be calculated. For vehicular traffic, free-flow time can be reasonably assumed as the desired speed divided by the extension of the circulation zone (i.e., the time needed to cross entire shared space by the desired speed). Consequently, time delay for vehicle i is computed according to Eq.(4.1) (for convenience, desired speed v_d is assumed to be the same for all vehicles):

$$d_i = t_i - \frac{v^d}{l} \tag{4.1}$$

The computation of this measure is straightforward. To show its quick applicability, delay time was computed for all vehicles, discerning per lane. Desired speed was assumed as the 85^{th} percentile of instant speeds within all the circulation zone as computed in Sec. 3.4. This value resulted in approximately 17 km/h and is slightly lower than the posted speed limit. Moreover, l correspond to the length of the circulation zone (63 m). The histogram of delay time (see Fig. 4.2, left) reveals how lane 1 (direction north-east) is more congested than lane 2 (direction south-west); in lane 2, the mode is close to 0; in lane 1, it lays in the range of 5 to 10 s (lane 1indeed has higher traffic volumes). Moreover, in the time profile (see Fig. 4.2 right), it is noted that, in lane 1, temporary congestion is experienced on more than one occasion (mean delay times exceed sometimes 30 s), while lane 2 traffic is mostly stable (maximum *LOS* is C).

With regard to pedestrians, the computation of delay time is complicated by non-lane-based behaviors. The value of l cannot, in fact, be defined uniquely, but needs to be specified for every pedestrian as desired path length l^d. Assuming that, in free-flow conditions, pedestrians use the criteria of the shortest path to minimize efforts, the direct line between origin and destination is assumed as the desired path. Therefore, the value of l refers to this

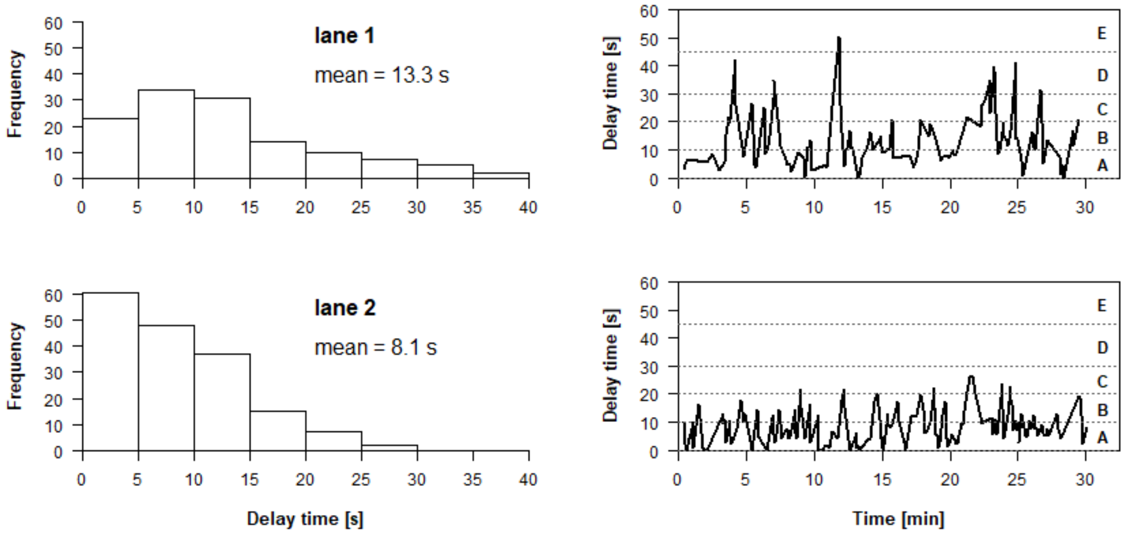


Fig. 4.2. Delay time for vehicles separated by lane (lane 1 above, lane 2 below): histogram (left), temporal profile (right)

path. For consistency, desired walking pace should also be pedestrian-specific. Therefore, delay time is computed according to Eq.(4.2):

$$d_i = t_i - \frac{v_i^d}{l_i^d} \tag{4.2}$$

The presence of v^d and l^d denotes that delay time is a matter both of decelerations and deviations, which are typical evasive strategies when conflicts against vehicles are encountered. Decelerations usually occur by perpendicular conflicts; instead, if pedestrians are crossing diagonally, they prefer to postpone the crossing, then to walk parallel to the street axes to let the car pass, and finally to cross perpendicularly. In both cases the evasive action affects the delay time to reach the destination. An example of this situation is provided in Fig. 4.3 and was observed in the case study. The arrival of the vehicle above influence the walking pace, which is reduced (till 0.8 m/s) before entering the circulation zone. Successively, when the vehicle decelerates, desired walking pace is restored (till 1.25) but the walking direction is set more perpendicularly in order to fasten the crossing movement.

However, while the computation of the desired path length is straightforward, the desired speed is more difficult to calculate. Even without encountering conflicts during the trip, the walking pace is not steady but it oscillates due to the alternation of steps [78].

For this reason, we present a method for computing a pedestrian's desired speed. This method requires as input the instant speed at every time step, from which the instant acceleration can be inferred. An exemplary situation is taken to show the procedure. In this situation, the instant speed of the pedestrian at every time step is plotted over time (see

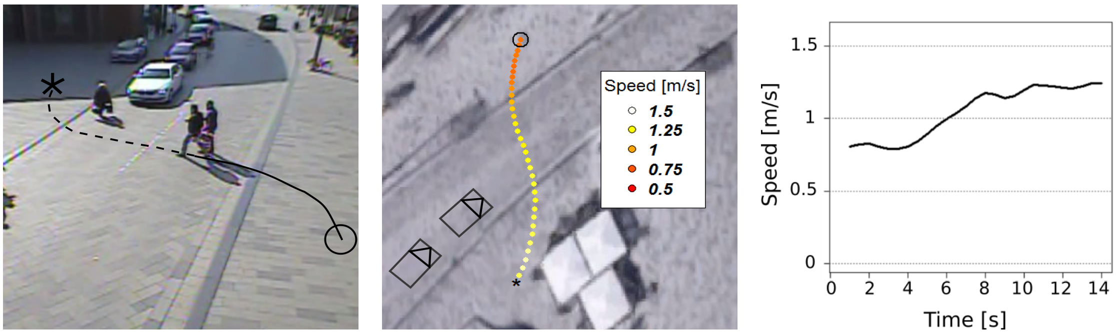


Fig. 4.3. Exemplary reaction of a pedestrian in a conflict with a motorist. Overview on spatial and speed behavior.

Fig. 4.4 left). The profile is divided into three parts: (A) where speed decreases in reaction to a conflict situation; (B) where the pedestrian accelerates after the conflict is solved; (C) where the pedestrian walks undisturbed by approximately constant walking pace. The latter part corresponds to the free-flow condition and is the value to be inferred.

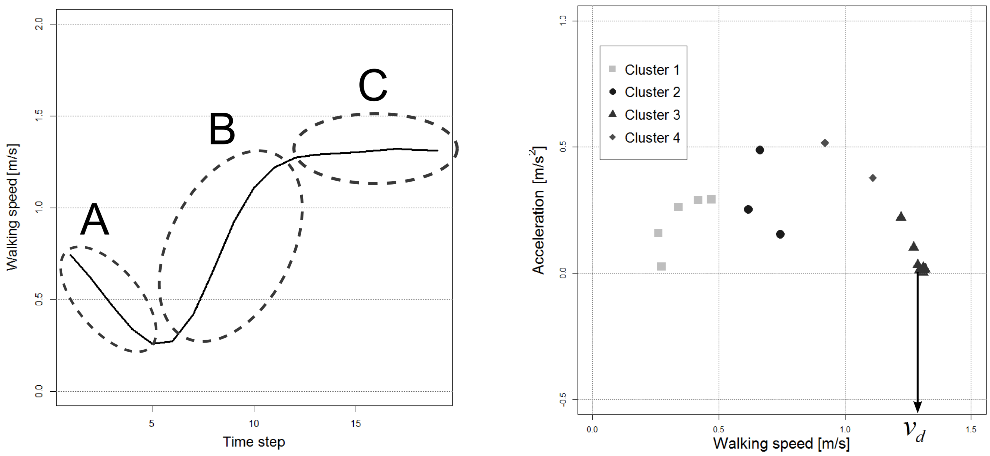


Fig. 4.4. Methodology to infer desired speed of a pedestrian: exemplary situation

This is carried out by a three-step methodology, which is described as follows.

Step 1: Clustering *K-means* algorithm is performed on the variables, i.e., walking speed and acceleration (Fig. 4.4 right). For every cluster j detected, the centroid is calculated with the values of mean walking speed v_j and mean acceleration a_j.

Step 2: Computation For every cluster j, the objective function k_j is computed [Eq.(4.3)]:

$$k_j(a_j, s_j, v_j) = \frac{a_j}{s_j v_j^4} \tag{4.3}$$

where s_j is the size of the cluster j. The principle behind this is that desired speed v_i^d is the highest speed during the trip (v_j is maximized), which remains approximately stable for a certain time interval (a_j is minimized and s_j is maximized). Because desired speed is usually greater than 1 m/s, the power is added to v_j to magnify the effect (the power of four was manually calibrated by comparison with reasonable results)

Step 3: Minimization The minimum value of k_j is assumed to be representative of the free-flow condition (Cluster 3 in the provided example, see Fig. 4.4 right).

In order to obtain more reliable results, the process is repeated three times by setting the number of clusters n_{cl} (see Step 1) to 2,3 and 4. Finally, the value of v_j with the relative minimum k_j is assumed as the desired speed. In the provided example, the minimum was found to be the Cluster $j = 3$ with $n_{cl} = 4$, which corresponds approximately to the (C) of the speed profile (see Fig. 4.4 left).

This method was applied to all pedestrians in the data set. The histogram of desired speed (see Fig. 4.4 left) shows a bell-shaped curve, with mean value 1.36 m/s and standard deviation 0.29 m/s. Note that this result is similar to the findings of Weidemann [83], in which mean speed and standard deviation were, respectively, 1.34 and 0.26. Finally, the delay time is computed according to Eq.(4.2) (see Fig. 4.4, left). When delay was found to be negative, which occurred in less than 1% of cases, the value was adjusted to 0.

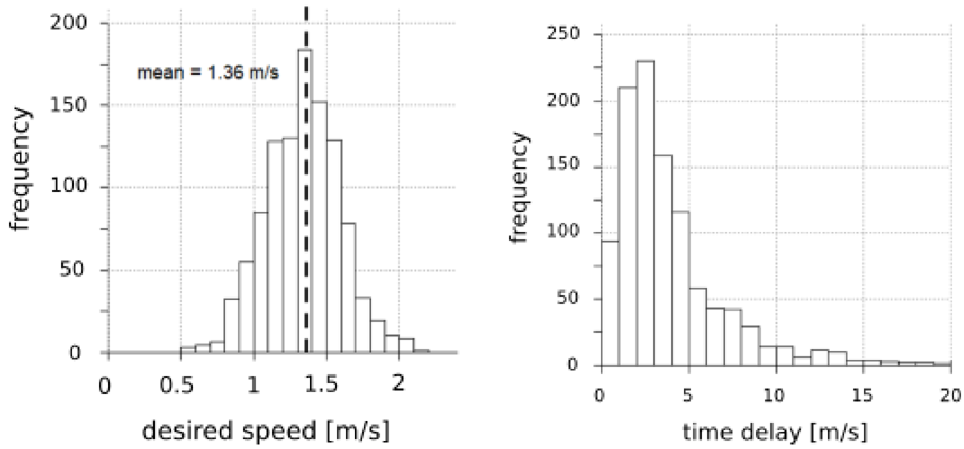


Fig. 4.5. Histograms of desired speed (left), time delay (right) of pedestrians

4.1.2 Limits of delay time for pedestrian traffic quality

After calculating delay times both for vehicles and pedestrians, the suitability of this *MOE* - and eventually the limits - in representing traffic quality in shared spaces is investigated.

With regard to vehicles, shared spaces are essentially traffic corridors with the function of movement. Except for loading and unloading operations (i.e., people and goods) motorists are interested in minimized travel times. High delays (i.e., many pedestrian crossings, queues) reduce the attractiveness of shared spaces for motorists, making alternative routes more preferable. This means that delay time reproduces traffic quality and is reasonable as *MOE* for vehicles. For this dissertation, vehicle delay is abbreviated to the acronym VD.

Instead, as discussed in Chap. 2, pedestrians in shared spaces shall be provided increased comfort while walking and moving through the space. Therefore, it is arguable that time delay would capture these aspects. To confirm this, exemplary crossing movements of pedestrians were extracted through video material and briefly discussed.

The first example includes Situation 1 (Figs. 4.6a and 4.6b) and Situation 2 (Fig. 4.6c and 4.6d), in which pedestrians reach the destination with approximately 1 s of time delay. In Situation 1, a couple of pedestrians are crossing the carriageway's area with the intention to accord priority to the black vehicle. The walking pace is low enough to give the motorist time to drive away. However, the driver suddenly decelerates (to let another pedestrian pass), forcing the pedestrian to deviate to the right. Despite safety not being compromised, the deviation was uncomfortable and unpleasant – also because of the presence of the white car approaching. In Situation 2 a pedestrian walks slowly, prudently, in order to find out if the upcoming car will yield or not. Successively, as the car decelerates, the pedestrian increases her walking pace and reaches the comfort zone. Compared to Situation 1, the quality of the movement is absolutely better: the movement is comfortable, the driver has decelerated well in advance and no other vehicle is present. However, delay time was equal.

Fig. 4.6. Delay time close to 1 second: Situation 1 (a and b) and Situation 2 (c and d)

Another example is given in the case of delay time close to 0, i.e. pedestrians have neither deviated, nor decelerated. In Situation 3 (see Fig. 4.7, left) a pedestrian exploits the time gap between cars to reach the comfort zone, tenaciously. The risk of collision is high because the cars drive at around 20 km/h, in both lanes. Moreover, a motorcycle passes by and a parked car disturbs the crossing. In Situation 4 (see Fig. 4.7, right) the space is clear, and no car is there; moreover, the presence of other pedestrians nearby instills serenity to the pedestrian, as if he were in a pedestrian zone. The conclusion is that, in Situation 3, traffic quality can be considered lower.

The conclusion is that, by simple visual comparison, time delay may not solely capture traffic quality in shared spaces. The aspects related to comfort must be included in the evaluation.

Fig. 4.7. Delay time close to 0: Situation 3 (left), Situation 4 (right)

The question is which of them is relevant and how can a mathematical formulation be provided.

4.1.3 A new pedestrian performance indicator

The identification of relevant aspects of traffic quality is covered in this section, which focuses on the process of construction of a new *MOE* for pedestrians in shared spaces.

Two main aspects are considered for this purpose. The first is the delay time, which is objective and directly measurable. The motivation is that, logically speaking, reaching the destination in a reasonable time and without excessive delays is an objective for pedestrians in every context. The second is the comfort of the trip, which is subjective and more difficult to capture.

Regarding the last point, Kaparias et al. [44] dealt with this issue by investigating what influences the perception of walking comfort in a shared space, including person-, context-, and design-specific factors. From the survey, it emerged above all that low vehicular traffic and high pedestrian traffic positively contribute to the perception of comfort. This and other findings were useful in this work for the formulation of comfort-related indicators. Three classes of parameters are supposed to be related with walking comfort. These are related to:

Traffic Environment (*TE*) The number of different types of road users around. In fact, many vehicles can be intimidating, while many pedestrians can increase the perception of confidence.

Interaction with Vehicles (*IV*) Interacting with vehicles generates apprehension for safety reasons. The more conflicts are severe, the more a collision is close, the more pedestrians feel unsafe.

Physical Movement (*PM*) To avoid collisions, walking direction and pace must be continuously adapted, which results in physical discomfort when performing evasive actions.

It is noted that this classification is consistent with the definition of the objectives of shared space design (see Sec. 2.2.2). In fact, *TE* focuses on the reduction of vehicle dominance (Objective 1), in particular with the number of vehicles. Instead, *IV* and *PM* focus on space sharing (Objective 2), respectively on road users' interaction and the consequent evasive actions, which cause a decrease in the level of path directness.

Formulation

The formulation of comfort aspects, provided above, can be appropriate for every type of shared space. However, this work deals with shared streets where a pedestrian trip essentially consists of crossing the carriageway's area. For this reason, parameters are formulated focusing on this specific movement of pedestrians. An overview of all parameters, which are assumed to potentially affect traffic quality, is given in Tab. 4.2. Parameters are successively formulated and discussed. The principle is that, for every pedestrian trip, a single value of all parameters in the table is provided.

Factors	Acronym	Unit
Time delay	D	s
N° of vehicles	TE1	-
N° of pedestrians	TE2	-
Conflict duration	IV1	s
Lowest minimum future distance	IV2	m
Time to Lowest Minimum future distance	IV3	s
Variation of direction	PM1	$\sqrt{rad * m}/s$
Variation of speed	PM2	$\sqrt{m}/s$

Tab. 4.2. Development of a new MOE for pedestrian traffic quality: overview of parameters considered

The parameters belonging to the field *traffic environment* concern the presence of different type of road users. At every time step ts in which the pedestrian is moving (from ts_A to

ts_B), the number of road user n_{ts}^k of type k within a radius d^k is computed; successively, the value is averaged for the whole time interval according to Eq.(4.4):

$$TE^k = \frac{\sum_{ts=ts_A}^{ts_B} (n_{ts}^k \mid d \leq d^k)}{ts_B - ts_A} \tag{4.4}$$

This value is calculated for vehicles (*TE1*) with d^k equal to 25 m, while for pedestrians (*TE2*) d^k was assumed 15 meters. The idea behind this is that, when crossing the circulation zone, pedestrians generally look both ways to check for motorized vehicles; in doing so, they extend the perception range to evaluate if a motorized vehicle - despite distance - can represent safety concerns.

The interaction with vehicles is represented by three parameters, which capture different aspects of traffic conflicts. According to Gettman and Head [28], a conflict is defined as "an observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged". This means that a conflict occurs when the relative distance between road users dangerously drops and is expected to be around zero - in the near future - if the behavior of road users remains unchanged. Given that the relative distance between users can be easily calculated by considering a body's center of gravity, a collision is assumed to occur when this distance is below 1.5 m (vehicle plus pedestrian half-body). Instead, the "risk" of collision only may imply higher values of relative distance, i.e., a collision may not happen, but the risk exists. In line with this thinking, a small procedure was developed to infer if, at any time, two road users are in a conflict situation with each other.

The procedure requires as input the position of two road users at time step ts^* and in the last three time steps. The expected behavior is computed by fitting a cubic smoothing spline to the four input positions of each road users and then by predicting the future spatial behavior within the next 8 s. Successively, at every future time step, the distance d between users is calculated. If the distance is found to be below a given threshold d_{lim} in any of the future time steps, a conflict occurs. In line with the expression "risk of collision", d_{lim} was set to 5 m. In this case, three values are saved:

- The current time step ts^*;
- The minimum distance d_c^* (which is lower than d_{lim});
- The temporal proximity t_c^* to the moment of minimum distance.

Given a pedestrian crossing the circulation zone, this process is repeated for all time steps and with respect to all road users around the pedestrian. This allows us to estimate, for every conflict detected, its temporal length as well as its evolution in time. At the end of the trip, the following parameters are saved for the pedestrian under analysis:

- **IV1**: The number of time steps, in which the conflict detected had $d_c^* < 2m$ and $t_c^* < 5s$. This represents a conflict with high probability of collision and very close in time.
- **IV2**: The lowest d_c^* among all conflicts.
- **IV3**: The respective t_c^* in the moment of lowest d_c^*.

IV1 was formulated according to the idea that the constant states of conflict with imminent collision could generate discomfort. The longer it lasts, the lower the comfort. I*IV2* and *IV3* focus instead on the conflict with the highest collision probability. Low values of *IV2* and *IV3* can possibly decrease comfort.

Interaction among users is performed by deviations and changes in walking speed, whose intensity is determined by many factors, e.g., the type of interactive users, the conflict's severity. In light of this, discomfort is caused by the physical effort needed to modify the current behavior. Deviations from current direction are particularly unpleasant if they are rapid and immediate; moreover, the discomfort increases as the walking pace rises. To obtain an indicator that accounts for these elements, the change of direction dir'_{ts} is computed at every time step ts as in Eq.(4.5):

$$dir'_{ts} = \frac{\mid \hat{e}_{ts} - \hat{e}_{ts-1} \mid}{T} \tag{4.5}$$

where $\hat{e}_{ts}$ is the normalized vector of direction at time step ts, $\hat{e}_{ts-1}$ in the previous time step, and T is the time length of a time step in seconds. The squared root of dir'_{ts}, weighted for the walking pace v_{ts}, is summed up for the time interval between the start of the first conflict ts_{CA} and the end of the last conflict ts_{CB} [Eq.(4.6)]. The definition of conflict corresponds to that used for parameters *IV* (d_c^* lower than d_{lim}).

$$PM1 = \sum_{ts=ts_{CA}}^{ts_{CB}} \sqrt{dir'_{ts} \cdot v_{ts}} \tag{4.6}$$

Given that the $dir'_{ts} \cdot v_{ts}$ often return values close to 0, the squared root was applied to magnify the contribution of this term. In this way, small deviations with high speed (or deviations with low speed) would also provide a significant contribution when the user is in a conflict situation, in comparison with 0 values when conflict are not occurring.

Variations of speed can be assumed as unpleasant only when negative, i.e. when they imply decelerations. The term PM2, which represents discomfort due to the modification of speed, is computed in analogy with PM1 [Eq.(4.7]):

$$PM2 = \sum_{ts=ts_{CA}}^{ts_{CB}} \sqrt{a_{ts}} \tag{4.7}$$

where a_{ts} is the acceleration at time step ts. The square root was also applied here to magnify accelerations close to 0.

For the sake of clarity, readers are reminded that the developed parameters are travel-related and refer to a single crossing pedestrian. This means that, given a collection of points at every time step (i.e., the trajectory of a pedestrian and the progress over time), one single value is computed for every parameter listed in Tab. 4.2.

The set of parameters was computed for every pedestrian observed in the case study. The boxplot in Fig. 4.8 provides an overview about the distribution of values. If a pedestrian did not experience any conflict during the travel, *IV2* and *IV3* were assumed to be, respectively, 5 and 7.61 (which was the highest t_c^* detected among all). Readers must be reminded that parameters have different units of measurement, and this diagram was created to provide the reader an order of magnitude.

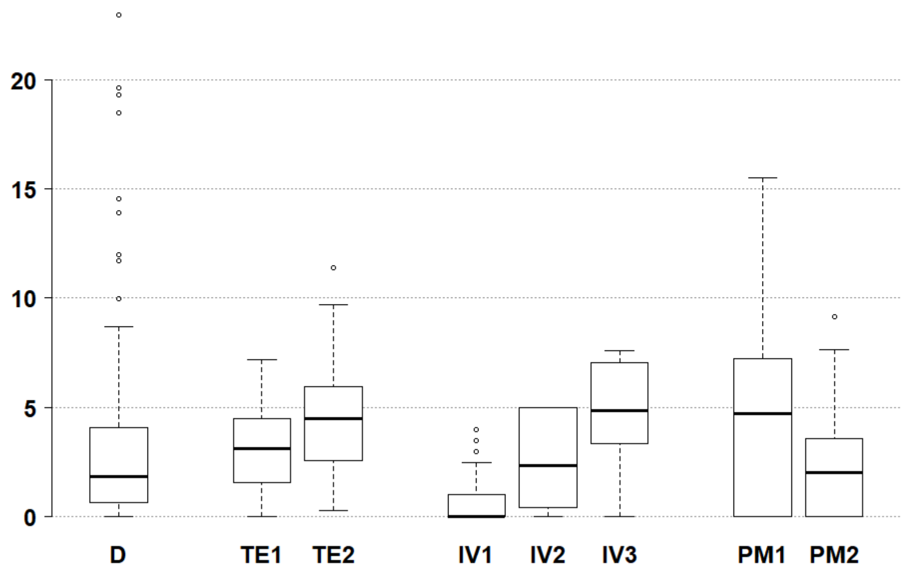


Fig. 4.8. Boxplot of the developed factors computed for all pedestrian trips observed in the case-study

Given the developed parameters, the aim is first to detect which among them - and to what extent - effectively influence the quality of traffic. This issue is covered in the next subsection and includes a questionnaire, in which a group of respondents was asked to evaluate the crossing of pedestrians, and a regression analysis, which is needed to calibrate the model and to construct the new *MOE*.

Survey design by questionnaire

A survey was carried out to detect which factors, among those developed in Sec. 4.1.3, can represent traffic quality in shared spaces. This step is carried out by asking a group of respondents to watch video sequences in which a pedestrian crosses the circulation zone and to evaluate the quality of the trip by a discrete scale. The sequences selected were 120; they started as the pedestrian appeared on the screen and ended as he disappeared on the opponent side of the road. The duration of the sequence depended on the time needed by the pedestrian to cross and varied between 0 and 22 s. To choose 120 representative video sequences, the *K-means* clustering method was used by considering all variables in Tab. 4.2. Once each video cluster number was assigned, the video with lowest distance to the centroid was chosen. This operation was carried out to consider all different cases and not to neglect any combination of factors.

A group of 60 respondents was selected for the survey by mixed attributes of gender (male 53%, female 47%), age (between 13 and 70 years old), and personal knowledge of shared spaces (from high knowledge to “ever heard”). Respondents were first asked to watch a brief Power Point presentation, which included an explanation of the subject of the survey and technical information to perform the evaluation. This presentation consisted of 16 slides and is reported in Appendix C. In the presentation, to familiarize respondents with the evaluation, two video sequences were shown. In the first, a pedestrian crossed the road at a time where no motorized vehicle was present. The second displayed a group of pedestrians who tried to cross the road in a congested situation: One pedestrian took advantage of the short temporal gap among vehicles to pass through, while others remained safely on the margin of the circulation zone, waiting for the cars to pass. The situations included subtitles, which made the respondents note indisputable attributes (e.g., “no car is present”, “vehicular traffic is dominant”, “crossing is easy/fast/complicated”) and without directly referring to the hypothesized elements of discomfort. Finally, respondents were asked to evaluate the crossing movement in 12 video sequences by a grade on a five-step discrete scale, including very pleasant (++), pleasant (+), neutral (0), unpleasant (-), very unpleasant (- -). Once the presentation was over, the same video sequence with a crossing pedestrian was shown to all respondents. Successively, they were asked to provide a grade with some motivation. This step was needed to make sure that the respondent has correctly understood his (her) task. Finally, each respondent received a list of 12 videos to evaluate. The sequences were randomly selected but with the requirement that at the end of the survey each video had to be evaluated six times in the overall by different respondents. Before watching the video, a screenshot of the first video frame was shown, where the pedestrian under focus was circled. To facilitate the evaluation, the respondents were allowed to view the video sequence as many times as desired.

Calibration

For every crossing situation, an overall score in the range between -2 (- -) and +2 (++) was computed as the average score given by respondents. A multilinear regression was then performed with all the predictors (see Tab. 4.2). In order to have a meaningful interpretation of the intercept estimates in the multilinear model, predictors were centered on their mean. The aim was to detect which variables influence the quality of the crossing movement and then to fit a multilinear model to predict the response.

Before starting with the regression, predictors were checked for multicollinearity by computing the correlation matrix with the Kendall method. The highest value among the off-diagonal coefficients is in regard to predictors PM1 and PM2 (0.65) and could be explained by the fact that deviations and deceleration (which are both possible reactions to conflict situations) are usually performed together. Medium correlation (-0.56) was also detected for the pair *IV1-IV2*: the reason could be that the duration of severe conflicts is related with its severity (for low values of the minimum distance, more time is needed to solve the conflict). Non-negligible correlation was also found for the pairs *IV2-PM1* (-0.49) and *IV2-PM2* (-0.46). The reason could be that more intense evasive actions (deviations or decelerations) are needed when a collision is probable. Despite any variable appears to be highly correlated with any other, the off-diagonal coefficients suggest that the significance of single predictors in the regression model could be partially hidden by another one. For this reason, the regression is not performed just once (with all predictors together) but at different stages, where at every stage only the most significant predictor is added. This is needed to include in the model formulation as few variables as possible and only the most significant ones. In the first stage, a set of linear regressions is performed considering one predictor at a time. The regression is carried out in R-statistics [66] by the function *lm*, which uses the least squared method to estimate the intercept k_0 and the coefficient k_{p1} of each predictor $p1$. The result is shown in Tab. 4.3.

Analysis of *p*-values shows that all predictors except for *TE2* are significant in the single model. High *D*, *TE1*, *IV1*, *PM1* and *PM2* generate discomfort, while high *IV2* and *IV3* increase comfort. These results confirm the expectations. However, the novelty is that the number of pedestrians seems not to affect traffic quality.

Predictor $p1$	$Adj.R^2$	k_{p1}	Std. Error	t-statistic	p-value
D	0.454	-0.13	0.01	-10.00	**0.0000**
TE1	0.255	-0.29	0.04	-8.16	**0.0000**
TE4	0.000	0.01	0.03	0.42	0.6755
IV1	0.104	-0.27	0.07	-3.85	**0.0002**
IV2	0.297	0.24	0.03	7.16	**0.0000**
IV3	0.044	0.09	0.04	2.56	**0.0000**
PM1	0.300	-0.13	0.02	-7.21	**0.0000**
PM2	0.296	-0.22	0.03	-7.15	**0.0000**

Tab. 4.3. Regression analysis for linear models $k_0 + k_{p1} \cdot p1$ (predictors $p1$ are considered one at a time)

Final formulation

In order to keep the model simple, predictors were added one at a time. On each round i regression analysis was performed by simple linear models by testing predictors $p1$ separately. If more than one predictor was found to be significant, the one with the highest R-squared was chosen. In the first round (as in Tab. 4.4), delay time *D* was included in the model, as it has the highest adjusted R-squared (0.45). Successively, the analysis is repeated, as shown in Tab. 4.4 and new predictors were added one by one. From the second round, the complete tables with statistical values (i.e., multiregression analysis with more than one variable) are reported in Appendix D.1.

i	Model	pi	R^2	Std. Error	k_{pi}	t-statistic	p-value
2	$.. + k_{p2} \cdot p2$	$p2 = IV2$	0.602	0.19	0.03	6.83	0.0000
3	$.. + k_{p3} \cdot p3$	$p3 = TE1$	0.659	-0.18	0.03	-5.69	0.0000
4	$.. + k_{p4} \cdot p4$	$p4 = IV3$	0.675	0.07	0.02	2.61	0.0102

Tab. 4.4. Regression analysis for multilinear models and significant variable chosen at every round i

At round i=5, no variable was found to be significant. This may happen because some predictors mask the effect of other predictors, which are already included in the model. In summary, by including in the model four variables, the multilinear model achieved an R-square of 0.675. This represents high improvement with respect to the single model with time delay *D* only, which has an R-squared of 0.454. This means that considering only delay as *MOE*, only 45.4% of the response would be explained by the model. By adding *IV2*, *TE1*, and *IV3*, the part explained increases of 49%. This is a demonstration that delay time is not capturing the whole quality of movement and is the motivation for refining and integrating the *MOE*.

Finally, the model is reformulated including only these four variables [Eq.(4.8)].

$$y = 0.883 - 0.118 \cdot D + 0.12 \cdot IV2 - 0.147 \cdot TE1 + 0.073 \cdot IV3 \tag{4.8}$$

The model returns 0.883 as baseline, high *D* and *TE1* makes traffic quality decrease, and high *IV2* and *IV3* makes it increase. However, it may happen that values fall around the range [-2;2], which were the boundaries imposed in the evaluation by the questionnaire. For this reason the logit transformation was applied to the variable y in order to scale the value between 0 and 1. This operation returns the final value of pedestrian *MOE* and is called pedestrian comfort (PC) [Eq.(4.9)].

$$PC = \frac{e^y}{1 + e^y} \tag{4.9}$$

To test the developed indicator, PC was computed for the very pedestrians shown in Fig. 4.6 and Figs. 4.7. The results (see Tab. 4.5) confirm the expectations described in Sec. 4.1.2: The quality of Sit.2 is better than Sit.1, despite the higher delay time; moreover, Sit.4 is much better than Sit.3. Finally, the indicator assigns higher quality to Sit.2 (with *D*=1.29) in comparison with Sit.3 (*D* close to 0), confirming that lower delay time does not necessarily correspond to higher *LOS*.

Situation	*D*	IV2	TE1	IV3	y	PC
1	0.98	1.68	4.30	0.60	0.38	**0.59**
2	1.29	1.48	2.00	2.80	0.82	**0.69**
3	0.10	1.15	3.95	1.27	0.42	**0.60**
4	0.08	5.00	0.21	7.61	1.44	**0.81**

Tab. 4.5. Pedestrian score computed according to Eq.(4.8) for the situations described in Sec. 4.1.2

Equation (4.8) considers the intensity of conflicts (*IV2* and *IV3*) as variables. However, in the course of this thesis, a conflict-free formulation of comfort will be required (motivations will be provided accordingly). For this reason, the multilinear regression was repeated from scratch by excluding the parameters of Class *IV*. The result is an alternative multilinear regression model, as specified in Eq.(4.10). Moreover, all statistic values from the multilinear regression are reported in Appendix D.2.

$$y = 1.702 - 0.116 \cdot D - 0.28 \cdot PM1 - 0.107 \cdot TE1 \tag{4.10}$$

It must be noted that the formulation includes only three variables instead of four, while the R-squared is slightly lower (0.667). This formulation is also tested in the same situations.

Situation	*D*	PM1	TE1	y	PC
1	0.98	2.58	4.30	0.41	**0.60**
2	1.29	1.65	2.00	0.88	**0.71**
3	0.10	0.88	3.95	1.02	**0.74**
4	0.08	0.63	0.21	1.49	**0.82**

Tab. 4.6. Pedestrian score computed according to Eq.(4.10) for the situations described in Sec. 4.1.2

It can be noted that in Sit. 1,2, and 4, the PC returns similar values to those in Tab. 4.5. The only value that differs is that in Sit.3 (the "brave" pedestrians that walked through traffic). This was predictable because this alternative formulation only captures the reaction to conflicts (expressed by parameters PM) but not the characteristics of the conflict (parameters *IV*). The pedestrian in Sit. 3, indeed, has taken no reaction even if conflict severity was considerable.

4.1.4 Level of Service definition

Traffic quality measures for shared spaces were investigated in the previous sections. In summary, delay time was assumed as suitable for vehicles because it reflects the function of movement. Nevertheless, for pedestrians, these measures were found not to be comprehensive of the overall quality and were integrated with aspects of comfort. As a result, suitable *MOEs* for shared spaces were identified as vehicle delay (VD) for drivers, and pedestrian comfort (PC) for pedestrians.

As mentioned in Sec. 4.1, *MOEs* are usually converted in terms of Level of Service (*LOS*) to obtain a more straightforward interpretation. In light of this, a classification is proposed here for the identified traffic quality measures.

Time delay for vehicles is a function of the length of the road section which is shared with pedestrians. By considering a standard free-flow speed, Vehicle *D*elay can be specified in relation to free-flow time (t_{ff}), i.e., the time needed to drive the entire road section at free-flow speed. For the sake of clarity, a value of 100% means that driving the shared space has taken twice as long as driving it at free-flow speed. *LOS* thresholds are established in Tab. 4.7 and consider the *LOS* inadequate (level E) when the delay time exceeded twice the free-flow time (t_{ff}). In the case study, this consists of an average delay time of almost 27 s, whereby 13 s were approximately needed to drive the whole shared space at free-flow speed (17 km/h).

Level of Service	Vehicle *D*elay (V*D*)
A	$\leq 50\%\ t_{ff}$
B	$\leq 100\%\ t_{ff}$
C	$\leq 150\%\ t_{ff}$
D	$\leq 200\%\ t_{ff}$
E	$> 200\%\ t_{ff}$

Tab. 4.7. Level of Service criteria for vehicles

The thresholds for pedestrian *LOS* were chosen arbitrarily by visually analyzing pedestrians crossing the shared space. In the case of high delay and low comfort (which were clearly observable), the *LOS* of the crossing pedestrians was classified as insufficient (level E), and the corresponding value of pedestrian comfort (PC) was saved. By detecting many of them, the threshold for sufficient *LOS* was arbitrarily chosen at 0.45. Consequently, the levels from A to *D* were fixed at increasing steps of 0.1. The Level of Service criteria is resumed in Tab. 4.8.

Level of Service	Pedestrian Comfort (PC)
A	> 0.75
B	> 0.65
C	> 0.55
D	> 0.45
E	≤ 0.45

Tab. 4.8. Level of Service criteria for pedestrians

As a conclusion of this section, the established traffic-quality indicators were computed for every road user. The average value was found to be 10.34 s for V*D* and 0.691 for PC, which correspond respectively to *LOS* B for both transport modes. The distribution of values is shown in Fig. 4.9 in the form of a histogram, in which the width of the bars was established in order to fit the *LOS* classes, which are printed behind. Both diagrams show that, in the case study, the distribution of *MOEs* is unimodal, with mode between 5 and 10 s for vehicles and 0.7 and 0.75 for pedestrians. Insufficient traffic quality (level E) was detected approximately in the 4% of road users, both for vehicles and for pedestrians, while level A was reached, respectively, in the 38% and 31% of cases.

4.2 Traffic Safety

Road accidents are direct measures of traffic safety. To investigate safety at specific locations, e.g., intersections, traffic engineers typically investigate historical crash records by analyzing

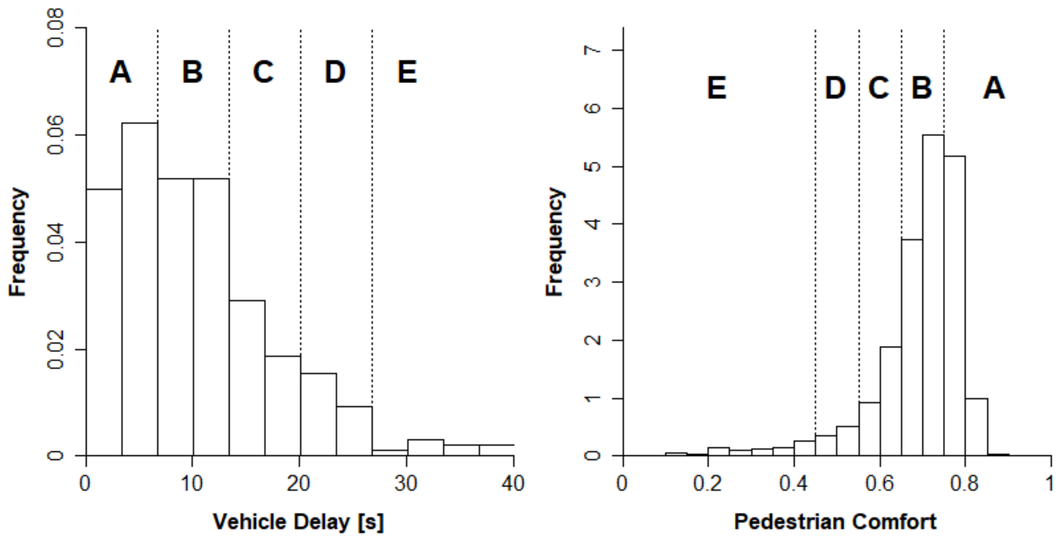


Fig. 4.9. Histogram of traffic quality of single road users in the case study: Vehicle *D*elay (left), Pedestrian Comfort (right)

accident dynamics and their consequences - i.e., fatalities and injuries. However, this approach has two main limits.

The first is that crash records are usually low-quality: Not all accidents are recorded. Moreover, error and incomplete information might be present. Finally, the approach used by police authorities to classify accidents might be unhelpful in pinpointing specific hazards [56]. The second is related to the sporadic nature of crashes, which are fairly infrequent, and a long time is needed to obtain statistical evidence.

In light of this, there is reasonable agreement on the usefulness of traffic conflicts as Surrogate Safety Measures (SSMs) [86]. That means, through the observation and analysis of conflict situations between road users, useful information about the accident potential of roads can be inferred. Common *SSMs* are listed below with a brief explanation.

Time To Collision (TTC) The time required for two vehicles to collide if they continue at their present speed on the same path [40]. It is a measure of temporal proximity to the collision.

Post Encroachment Time (PET) Time between the first road user leaving the common spatial zone and the second road user arriving at it [54]. It describes the evolution of the conflict situation.

Initial Deceleration Rate (IDR) . Intensity of the deceleration performed by a vehicle as a response to the risk of collision. It describes the intensity of the evasive action.

Vehicle Speed (VS) Speed of a vehicle at the time when evasive action is taken. It describes the current situation before evasive action is taken.

Many other measures have been proposed in the literature. The idea behind this is that different measures capture different aspects of the conflict, so that only the combined used of them can provide good insight into traffic safety. As noted by Gettman and Head [28], lower *TTC*, lower *PET* and higher *IDR* indicates high probability of collision, i.e., how probable a collision could result from a conflict. These measures indicate the severity of a conflict event. On the other hand, speed-related measures as VS indicate the severity of the potential collision that may result. By including the object's mass in the calculation, force of the impact and probable consequences can be calculated.

Traffic conflicts can be analyzed by field observations at specific sites to assess the safety of an existing road or facility. The behavior of road users is usually determined, in space and time, by manual tracking tools; successively the obtained data are submitted to post-processing algorithms for the automatic computation of *SSMs*. However, these methods are time-consuming because they require visual identification of conflicts and the tracking of an object's position at discrete time steps. Alternatively, computer-vision techniques can be developed for collecting conflict data automatically from video observations. Nevertheless, these systems are complex and cannot ensure high precision.

Microsimulation software can be used for this purpose. The advantage is represented by the possibility to assess traffic safety at the design stage, which can help in identifying the "safest" alternative. In fact, simulation is reproducible as many times as desired and different scenarios can be tested without excessive efforts. In other words, data are highly available and have high accuracy. However, as noted by Gettman and Head [28], all simulation models were designed assuming that drivers behave in a "safe" manner according to their particular driver characteristics. Further this is a long way from reality, in which conflict dynamics are far more diverse and drivers may also behave "unsafely".

SSMs are by definition indirect measures of safety, meaning that the relationship between conflict and crashes is not quantifiable absolutely. As a consequence, safety cannot be investigated absolutely but only relatively by comparing different scenarios with each other. In other words, by computing the number of conflicts, as well as the distribution of *SSMs*, one can only infer which design alternative is likely to be better than the other from a safety perspective.

4.2.1 Surrogate Safety Measures for shared spaces

Road users' interaction is the key element for successful shared spaces (see Sec. 2.2.2). When interaction occurs safely, pedestrians are encouraged to negotiate and share the space;

otherwise they would minimize it by giving cars priority. Consequently, the investigation of safety by conflict analysis techniques provides insight into the level of space sharing and, therefore, the success of space redevelopment. In comparison with conventional designed streets, shared spaces share peculiarities with regard to interaction. First, vulnerable road users as pedestrians are present. Second, the behavior is not lane-based, i.e. conflicts do not happen always at the same locations, as at pedestrian crossing facilities, but may happen everywhere in the shared zone. Moreover, conflicts and subsequent evasive actions may have different dynamics each time because priority rules are not fixed and reactions are variegated. This makes the analysis of conflicts more complex with respect to classical scenarios - not only in the practical computation of *SSMs* but also in the inferring conclusions and findings.

An exemplary conflict is chosen to show how *SSMs* can be practically computed in shared spaces. This consists of a couple of pedestrians who negotiate the space with motorists to reach the other side of the shared zone. The relevant part of the conflict lasts 7 s in total. A video frame around the half time of the conflict situation is depicted in Fig. 4.10, on the left. Speed profiles of road users - only one pedestrian was selected - are shown in Fig. 4.10, on the right, with different colors. At the beginning (around 1 s) pedestrians decrease their walking pace to understand the intention of the driver. Successively (2.5 s) the driver starts decelerating to yield to pedestrians. Finally (4 s) pedestrians accelerate again and complete the crossing movement.

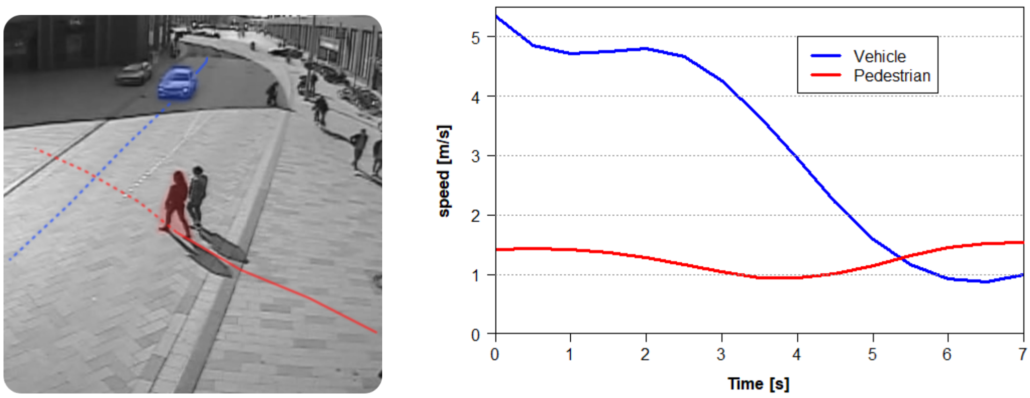


Fig. 4.10. Exemplary conflict situation: video frame (left), speed profiles (right)

To investigate the dynamic of the conflict, the statistics d_c^* and t_c^* as defined in Sec. 4.1.3 are plotted over time in Fig. 4.11. On the one hand, the statistic d_c^* expresses the *future minimum relative distance* between the pedestrians and the vehicle. As a way of example, the computation of this value at time 1.5 s returns in that the pedestrians and the vehicle will be "maximum" 1.3 m close at some point in the future if no one reacts. The word "maximum" means that this is the worst situation, i.e. the closest future distance, but no information about "when" is known. The temporal proximity, in fact, is provided by the other statistic t_c^*: at 1.5 s the *future minimum relative distance* is reached in 4.6 s. The combination of these statistics provides a full perspective in the dynamic of conflict: t_c^* says how distant in time is the worst situation going to happen, while d_c^* expresses how far in space would road users be from each other. In the selected situation, between 1.5 and 4 s road users have high probability of collision if behavior remains unchanged. This is stated by assuming that $d_c^* < 1.5$ corresponds to collision, as a body's or vehicle's barycenter is considered (horizontal dotted line in Fig. 4.11, left). Nevertheless, within this temporal range the values of t_c^* do not exceed 3.5 s, meaning that users have sufficient time to react. Finally, considering the evolution of the conflict situation, the increase in d_c^*, starting at 3.5 s reveals that a reaction has been taken (from one or both conflicting users) and danger pulls away.

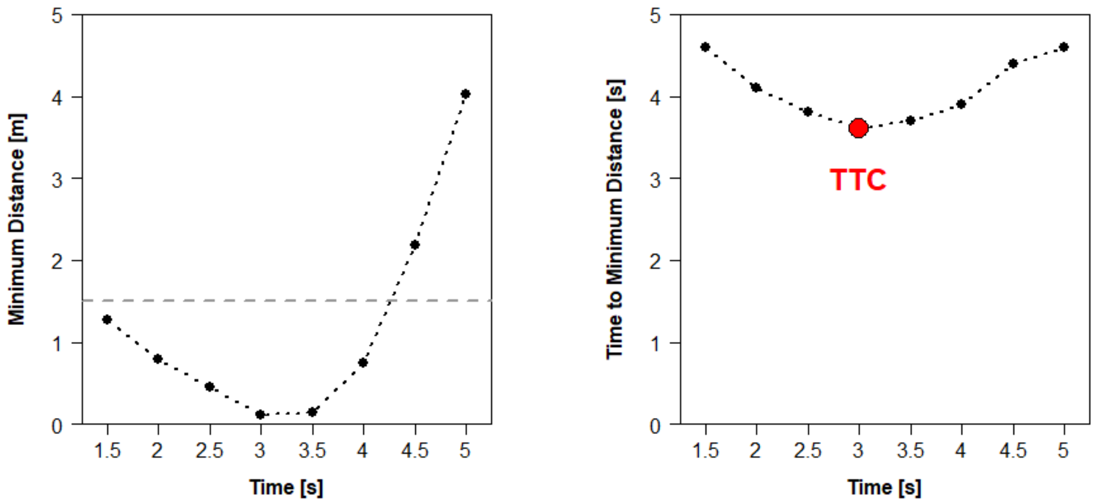


Fig. 4.11. Computation of conflict related variables: d_c^* (left), t_c^* (right)

In light of this, Time To Collision is computed as the lowest t_c^* within the whole conflict, in which d_c^* is below 1.5 (i.e. it would imply a collision). In this case, *TTC* is indicated in Fig. 4.11b and is around 3.45 s. The importance of this parameter to analyze safety in shared spaces has also been stated also by Kaparias et al. [45] within a study on pedestrian-vehicle conflicts. According to their methodology to classify conflict severity, *TTC* was actually the first factor to consider and was classified in long ($TTC > 2$ s), moderate (0.5 s $< TTC \leq 2$ s) or short ($TTC \leq 0.5$ s). The presented case, as predicted, does not represent any concern for safety.

Post Encroachment Time (*PET*) requires the identification of the "common spatial zone". This is determined by drawing the respective trajectories and detecting the point XP (X;Y), where they have crossed each other. Successively, the time in which conflicting road users have crossed XP is saved and the time lag is computed. *TTC* and *PET* both describe the severity of the conflict. More specifically, *TTC* measures the severity of the situation before the evasive action was taken, while *PET* focuses on the effective reaction of road users - once it has occurred. In the conflict under analysis this value was found to be around 4 s, which according to literature, does not represent any traffic concern.

Vehicle Speed (VS) captures the severity of the potential collision. In the presented example, the motorist is moving at 4.8 m/s before reacting and reducing the driving speed. As with Time To Collision, this measure focuses on the moment before the reaction was performed. It is particularly meaningful when applied to vehicle-pedestrian conflicts (i.e., in shared spaces) because it indicates the severity of the potential conflict on the side of the vulnerable road user. Pedestrians in fact report serious consequences even if the collision is light, while light collisions between vehicles usually result in damages without injuries.

Initial Deceleration Rate (IDR) is not straightforward to compute when dealing with shared spaces. The reason is twofold. First, other transport modes are present besides vehicles and they have different deceleration rates. As a consequence, it is difficult to compare situations in which different road users have decelerated. Second, pedestrians usually perform deviations as well as decelerations during conflicts. Deceleration rate would therefore not be representative for evasive action, as it would catch only one aspect of it, i.e., the speed perspective, not the spatial one. For these reasons, *IDR* is not considered here as an SSM for shared spaces. Nevertheless, future research can deal with the development of a holistic indicator for measuring reaction, independently from the road user considered and the type of reaction performed (deceleration as well as deviation)

4.2.2 Surrogate safety analysis by traffic microsimulation

In this dissertation we propose to employ *TTC*, *PET* and *IDR* together to evaluate traffic safety. Three main reasons are provided. First, they catch different aspects of interaction (before and after the evasive action). Second, they provide different aspects of safety (the probability of collision as well as the severity of the resulting collision). Third, they are easy to compute and do not need the development of any additional procedure.

Once these measures are collected on all of the individual conflicts that occur during microsimulation, the role of the analyst is to process this list of conflict event data into meaningful information about the surrogate safety [28]. In spite of this task being quite complex and requiring many specifications, we propose three general principles.

1. *SSMs* must be used to compare scenarios with each other - not to evaluate safety absolutely. This point has been previously discussed and is related to the fact that *SSMs* are *indirect* measures of safety by definition.

2. A large number of conflicts does not correspond to less safety. On the contrary, many low-severity conflicts can positively affect traffic safety. As explained in Sec. 2.2.2 and as demonstrated by Karndacharuk et al. [49], there is a correlation between the number of interactions occurred and operating vehicles speed. In other words, if

conflicts happen on a regular basis, drivers negotiate space with pedestrians by driving slowly.

3. For a given number of conflicts, higher *TTC* and *PET* and lower VS are preferable from the perspective of traffic safety.

Although a surrogate safety analysis will not be performed in this work for the case of shared spaces, microsimulation data for conventional scenarios (zebra crossing and refuge island) will be compared with each other from the traffic safety perspective in Sec. 7.3.2. Nevertheless, the discussed indicators are ready-to-use and can be applied to any data coming from shared space microsimulation.

5 Model development

This chapter is dedicated to the description of the developed modeling framework. The modeling approach is based on the Social Force Model (*SFM*), which was previously discussed in Sec. 2.4. Nevertheless, the classical *SFM* formulation needs to be integrated and extended to fit the shared space case.

In Sec. 5.1 the limits of classical *SFM* for shared spaces are presented via help of exemplary situations regarding road users' movement and interaction. Successively, a new modeling approach based on four layers is formulated: first, the *free-flow* layer (Sec. 5.2) to guide road users toward the destination; second, the *conflict detection* layer (Sec. 5.3) to identify conflict situations with other road users; third, the *conflict decision* layer (Sec. 5.4) to determine the type of reaction to be performed; fourth, the *conflict reaction* layer (Sec. 5.5) to compute the intensity of the chosen reaction. Finally, the implementation in a Java-based simulation tool is discussed (Sec. 5.6) .

5.1 Limits of SFM for shared space modeling

In the classical *SFM*, each road user i is assigned a value of desired speed ${v_i}^0$. Moreover, at every time step t, the versor $\vec{e_i}^0(t)$ describes the orientation of the desired direction [see Eq.(2.3)]. By the definition of "desired behavior", two opposite - and complementary - conditions can be identified: the first one, when the user is effectively able to accomplish this expectation in the next time step, referred to as *free-flow*; the second one, where the influence of other road users or obstacles force him to deviate or decelerate, which is referred to here under the heading of "interaction".

From a mathematical perspective, a road user at time step t^* will persist in the condition of *free-flow* at time $t^* + 1$ if the second and third terms on the right side in Eq.(2.5) are equal to zero. That means, at time step $t^* + 1$, the pedestrian will move again at ${v_i}^0(t)$ in the direction $\vec{e_i}^0(t)$ - or at least the road user will accomplish it soon, if he (or she) comes from a previous interaction situation. Otherwise, a force term will lead the user to a so-called *behavioral change*, and, at time step $t^* + 1$ the user will be in the condition of *interaction*.

In light of this subdivision between *free-flow* and *interaction*, which is purely a modeling issue, the description of model development in this chapter is split accordingly, i.e., the

	Classical *SFM*	Shared space requirements
Free-flow	• Motion oriented toward intermediate destinations	• pre-planning with smooth directional changes
Sec. 5.1.1	• all space is equal	• free-flow behavior is zone-dependent
Interaction	• stimuli are distance-based	• stimuli are conflict-based
	• reaction is automatic	• stimulus can also result in no reaction
Sec. 5.1.2	• reaction and stimulus have the same direction	• reaction and stimulus do not necessarily have the same direction

Tab. 5.1. Characteristics of the classical *SFM* and requirements for shared spaces

free-flow model and the *interaction* model (which includes conflict detection, decision and reaction). The analysis of classical *SFM* limitations, as summarized in Tab. 5.1, also follows this classification, while single points are discussed in the subsections. Successively, the developed modeling framework is presented in Sec. 5.1.3

5.1.1 Free-flow

In traffic flow theory, the term "free flow generally" refers to the condition of traffic when density is low and motorists have much freedom of movement. The term was coined in relation to LOS and capacities studies in freeway segments and specifically identifies the first part of the fundamental diagram, where flow rate and density are close to zero. In this condition, motorists can choose their preferred driving speed, which may depend on personal characteristics as well as the characteristics of the infrastructure, as lane width.

The concept of free flow is used in this dissertation with four main specifications. First, it is addressed to other types of road users besides motorists. Second, given the microscopical approach of the problem, it is referred to as the condition of a single road user instead of the state of traffic in general. Third, given that movement is not lane-based, it implies the choice of the desired path besides the speed. Fourth, it is not related to low flow rates, as in freeways, but to the absence of influential users around, i.e., no one around, or a few users, which reasonably cannot be influential. Therefore, in this work, a pedestrian is said to be in "free flow" if he/she has high freedom of movement and he/she can freely choose a preferred path and walking pace.

While the definition of the desired speed ${v_i}^0(t)$ of a road user is straightforward, the desired direction ${\vec{e}_i}^0(t)$ at every time step requires us to previously discuss which path would the road user choose if the user was completely free to choose. For simple geometries (e.g., open spaces), this passage is usually neglected, and the desired path is assumed as the direct line between the origin and the destination of the individual. When the environment gets more complicated, as a building with rooms, for example, intermediate targets are usually defined, according to which versor $\vec{e}_i^{\,0}(t)$ is oriented from time to time (see, for example, Roca et al. [68]). This would make the user reach an intermediate target and successively pass to the following one by a directional change. However, a first glance into free flow trajectories of pedestrians in the case study highlights the limits of this approach. To demonstrate this, all pedestrians in the first 5 min of video footage were selected, and their trajectories were saved. Successively, pedestrians who interacted and performed evident evasive actions were excluded. Finally, only trips with a considerable lateral distance between origin and destination were chosen (i.e., when the desire line was clearly diagonal to the circulation zone). The analysis of remaining trajectories (see Fig. 5.1, left) highlights two important issues:

- When road users' density is low - and, consequently, freedom of movement is high - individuals use to deal with directional changes gradually. Turning smoothly, instead of sharply, results in minimized physical efforts. By walking, it makes the pedestrian save energy. By riding or driving, it minimizes the centripetal acceleration.

- The circulation zone is less attractive for pedestrians. Even if vehicles are not present, this area is crossed by pedestrians more perpendicularly than in the remaining path. This introduces a heterogeneity in the space which must be accounted for in the path planning.

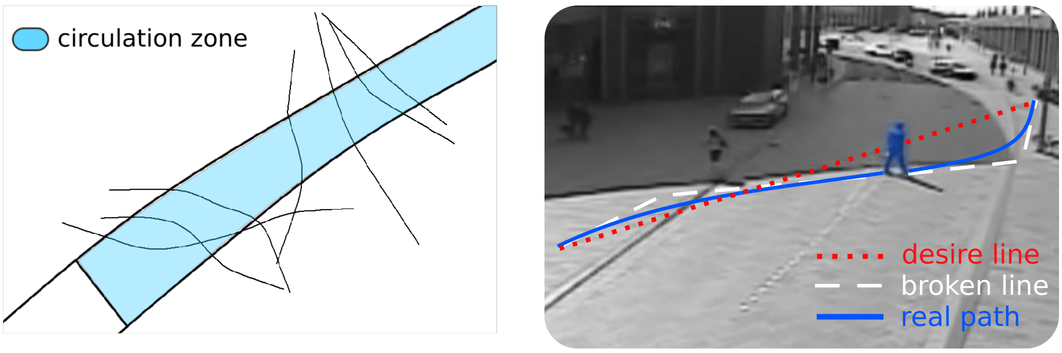


Fig. 5.1. Behavior of pedestrians in free-flow:
exemplary trajectories tracked (left), example on video footage (right)

This tendency is investigated further for a single pedestrian in Fig. 5.1 (right), who is marked in blue. The red dotted line represents the direct path from origin to destination (desire line), while the white dashed line includes intermediate destinations, which consider a shorter path in the circulation zone (broken line). However, the real path of the user in blue includes smooth deviations. In light of this, a path planning algorithm based on trajectory identification is proposed in Sec. 5.2, which includes the computation of intermediate destination based on space geometry and a zone-dependent path planning to account for the dangerousness of the circulation zone.

5.1.2 Interaction

The collision-avoidance mechanism among road users is controlled in the classical *SFM* by repulsive forces, which intervene as soon as the relative distance falls below a given threshold. In the model, each user monitors a circular zone around him/her - also referred to as *visual field*; once other users enter within this zone, he/she reacts accordingly. The decision whether or not to react is entirely up to the relative distance, with no matter about the relative position and the direction of movement. Since the extension of the visual field is restricted (usually a couple of meters), the classical *SFM* is considered a “short-range” model. Moreover, the reaction usually reflects the stimulus received. That is to say, the evasive action to avoid the collision is directed contrarily to the perceived stimulus.

These assumptions are quite realistic when dealing with evacuation problems, where pedestrians have to hurry to evacuate a building and to react instinctively. They are also quite realistic for simulation of high-density environments, as major events, where the restricted visibility inspires on to react only to short-range stimuli.

However, this model approximation is unrealistic when dealing with shared space modeling. Three main limitations are discussed below via real-world examples.

Limitation 1

According to the visual field marked by a dashed line (see Fig. 5.2, left), the red vehicle above should not be considered by the blue pedestrian. Nevertheless, the pedestrian looks at the vehicle in order to evaluate the next move. The reason is that, despite the relative distance between them being high, there is a concrete risk of collision to be carefully evaluated. In summary, long-range dynamics are not considered by the model, which is “blind” beyond a given spatial range.

Limitation 2

As the situation goes further (see Fig. 5.2 right), the blue pedestrian decides not to perform any reaction, even if the vehicle has not stopped. From a logical perspective, this behavior is reasonable: Given the presence of other two pedestrians and another vehicle ahead, the driver is expected to stop immediately. However, from a modeling perspective, this behavior contradicts the *SFM* ground principle that every stimulus generates a reaction.

Fig. 5.2. Exemplary situations: limitation 1 (left), limitation 2 (right)

Limitation 3

The blue pedestrian in Fig. 5.3, who is about to cross the road, is inspected. As the red car leaves, the pedestrian modifies his path by deviating to the left. However, from a modeling perspective, via classical *SFM*, the road user would receive a repulsive force according to the relative position of the vehicle (white arrow in Fig. 5.3, left), which would make the user decelerate but not deviate, as he actually did.

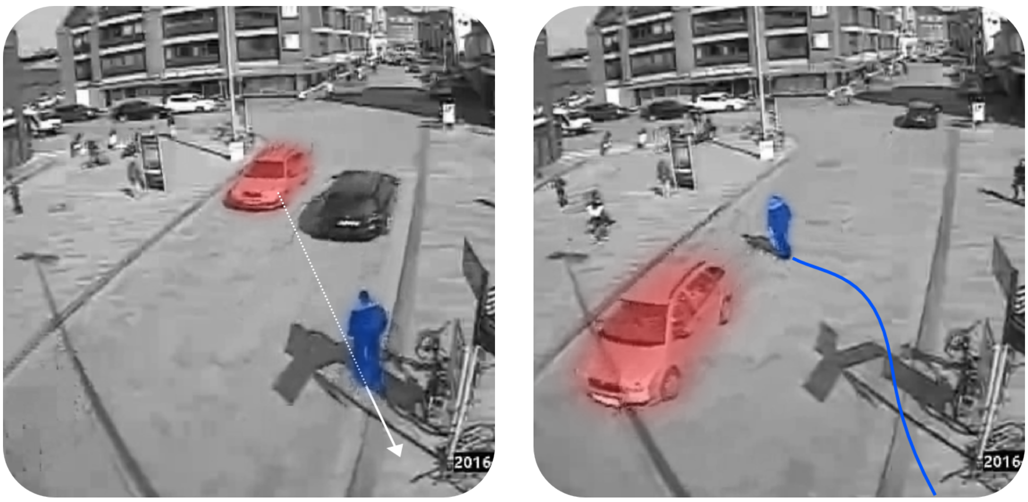


Fig. 5.3. Exemplary situation: limitation 3

After having shown exemplary situations, classical *SFM* limitations for modeling shared spaces are summarized below and constitute the motivation for the development of specific layers.

- Road users perform behavioral changes not according to the relative distance but to the eventuality of collision. In plain words, the perceived stimulus is conflict-based and not distance-based. For this reason, a *conflict detection* layer is developed.

- A stimulus does not necessarily imply a reaction. In case of conflicts, road users usually decide whether or not a reaction is needed. The decision is a trade-off between safety, which would imply a reaction, and comfort, which would make the user not react to preserve energies. A conflict decision layer is developed to account for this "filter" between stimulus and reaction. This layer answers the question of whether a reaction is needed and, successively, if yes, which type of reaction must be performed.

- The reaction is not always equal and opposite to the stimulus. Other aspects also determine the entity of the reaction and have to be investigated. This step is dealt with by developing a conflict reaction layer, in which the direction and intensity of the reaction is calculated.

5.1.3 Modeling approach

The developed approach consists of integrating the classical *SFM* with additional layers. From a pure mathematical perspective, new force fields are added to Eq.(2.2) to extend the model in the long-range. At every time step, the process illustrated in Fig. 5.4 is repeated, independently from the type of road user. First, the terms of the classical *SFM* are computed, both driving term and repulsive forces. Second, conflict situations are investigated. If no conflict is found, the equation is solved, and the new position of the road user is computed. If conflicts are found, it is determined which reaction has to be performed by the user. If this layer returns the decision not to react, the new position of the road user is computed; otherwise, the intensity of the evasive action is calculated in the *conflict reaction* layer. Therefore, the force is added to the *SFM* equation and the next position of the user is computed. Finally, the time step is updated and the process starts again.

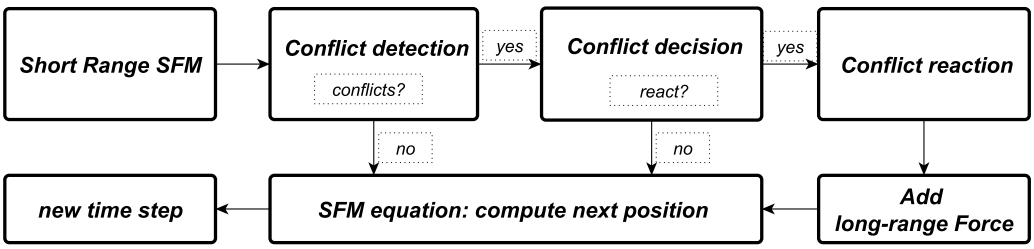


Fig. 5.4. Conceptual flowchart of the simulation steps

5.2 Free-flow layer

The basic principle of path finding is that road users tend to minimize travel time toward the destination, as far as possible. This principle applies to motorists on a macroscopic level, who seek for the shortest route available within the road network [21], and is also valid for pedestrians on a microscopic level, e.g., in a square or an open space. When people are sufficiently far away from each other, they choose the preferred path by following some basic rules. In particular, the following tendencies can be observed and are considered in the developed model.

- Pedestrians typically keep a distance to avoid colliding with obstacles, namely, walls and corners. Bosina et al. [18] investigated the amount of the distance and the effect of obstacles on the behavior of pedestrians downstream. The results have shown that a clearance distance is always observed, and its effective width depends on the pedestrian density.

- Directional changes are gradual. For a vehicle, this is needed to minimize the centripetal acceleration; for a pedestrian, it allows one to keep a constant pace, because sudden speed changes are uncomfortable and would require unpleasant modification of speed.

- As already shown in the previous section, pedestrians tend to adopt more perpendicular paths while crossing the circulation zone. The motivation is that, even if vehicles are not present, it is a psychological relief to leave this zone as soon as possible.

These factors represent the basic principle for modeling free flow trajectories for pedestrians. Instead, vehicles are restricted within the limits of the specific lane. As a consequence, the free-flow path can be approximated with the track of the roadway. However, parked cars or other road users can be present on the side of the road, forcing motorists to make smooth deviations. Therefore, the modeling of a free flow path will also regard vehicles.

5.2.1 Modeling approach

The algorithm for free-flow trajectory estimation consists of two separate phases: first, the computation of the shortest path; second, the adaptation of the resulted trajectory according to comfort and safety reason. The aim is to compute, for a given type of road user, the most realistic path from his/her standpoint to the destination. The developed method, which was part of the research project MODIS and was published in Pascucci et al. [59], is explained here for the case of pedestrians, whose path generation is trickier in comparison with that of vehicles.

The first step consists of the generation of a visibility graph over the 2D space according to the procedure of De Berg et al. [14], developed for the navigation of robots. Obstacles and non-accessible zones are transformed into polygons, whose edges represent point locations (or nodes). Successively, all visible nodes are connected with each other, forming a network of links, which does not intersect polygons. The result is a graph of intervisible locations called a "visibility graph", which constitutes the basis for path planning. An example of this procedure is provided in Fig. 5.5, left. The road user, who finds himself in the green point, has to reach the destination marked in red. The intervisible edges of walls and obstacles are connected with each other by gray links. This offers a series of path alternatives to the user to reach his/her target, which must be properly evaluated by a shortest path algorithm. This is performed here by the Dijkstra algorithm, which finally returns the shortest path, as indicated in Fig. 5.5 (left) by the blue color.

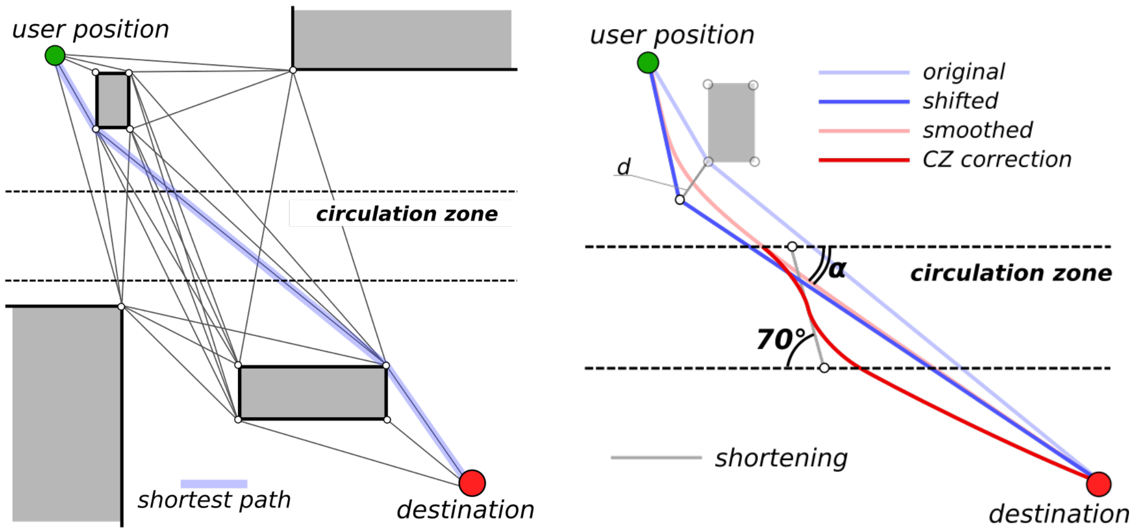


Fig. 5.5. Free-flow trajectory calculation:
visibility graph and selected path (left), path adjusting (right)

The selected path is successively adapted according to the observed tendencies listed in Sec. 5.2.

Initially, all inner path nodes are translated in the normal direction of the corresponding polygon for a distance d, here assumed to be 2 m. This step is shown in Fig. 5.5 (right) by the "shifted" blue line, in which the edges were shifted from the original path.

Successively, a realistic smooth path is computed by an edgewise calculation of point-to-point clothoids. Clothoids are widely used as transition curves for the design of highways or railroads and allow for driving without instantaneous steering but with constant curvature. Bertolazzi and Frego [15] developed an algorithm for computing clothoids between two points using four parameters, namely, the start- and end-point and -angle. In this way, the change of direction between two direct lines is smoothed, as shown in Fig. 5.5 (right) by the light red line, named "smoothed".

Finally, the path is adapted to account for the sense of unsafeness generated by the circulation zone. If the path crosses this area, the angle α between the tangent to the smoothed path and the border of the circulation zone is computed. If α is higher than 70°, then the path is "direct" enough, and no modification is needed. Otherwise, as in Fig. 5.5 (right), the path would require too much time to be traveled and must be shortened. In this case, a new shortening is computed (gray line), whose angle has 70° with the border of the circulation zone. Then the shortening is included in the smoothed path, and the clothoids are computed again (red line, "CZ correction"). The resulting path is called Free Flow Trajectory (*FFT*).

The procedure described was ad hoc developed to solve the path-planning issue for pedestrians. Nevertheless, the same procedure is also used for motorists except for the CZ correction. In fact, even if obstacles and walls are not present, it is common in the case of a parked car at the border, which forces vehicles to adopt a new free flow path to detour from the fixed obstacle. In this case, considering parked vehicles as obstacles, the developed procedure is applied anyway.

Once *FFTs* are defined for every road user, a value of desired speed ${v_i}^0$ has to be assigned. Research has widely investigated pedestrian walking pace in traffic environment. Daamen and Hoogenodoorn [23] studied walking speed in pedestrian-only environments. Fitzpatrick et al. [26] focused instead at traffic signals. Montufar et al. [53] studied the difference between the normal and the crossing walking speeds of pedestrians at signalized intersections. In the German context, we recommend a technical report for the Bundesministerium für Verkehr-, Bau und Wohnungswesen in which pedestrian speed has been collected in different context and for different purposes [2]. The aim of the analyst is therefore to understand the context of the shared space (e.g., the type of attractions around, the character of the street) and to set the suitable average walking pace of pedestrians accordingly. For the case study, the desired speed has been inferred from the speed analysis performed in Sec.3.4, where the 85th percentile of instant speed was discovered to be 4.73 m/s for motorists and 1.41 m/s for pedestrians. Moreover, to introduce randomness, a standard deviation of 0.25 m/s was assumed for both of them.

5.3 Conflict detection layer

The conflict detection layer is addressed to find situations that could lead to collisions among road users. Note that the expression "could lead" reflects the commonly accepted definition of *conflict* in traffic safety analysis, as stated by Amundsen et al. [3]:

> *"an observable situation in which two or more road users approach each other in time and space for such an extent that there is a risk of collision if their movements remain unchanged."*

The concept of “risk” is used because there is uncertainty about how people would behave if the movements effectively remain unchanged. In other words, it is impossible to split between a situation that would lead to a collision, but we can only refer to the “risk” of it. Moreover, even if a collision is unlikely in itself, the risk of collision still remains, as a road user can sometimes exhibit sudden and unexpected behaviors. Summarizing, it is difficult to effectively define what a “risk of collision” is.

Nevertheless, with the aim of modeling, we identify this condition by comparing the expected future behavior of two road users, with reference to the relative distance. For the sake of clarity, the situation is explained here for the case of a conflict between two pedestrians, but can also be applied to non-pedestrian users and generalized to multiple conflicts. The developed procedure, which is discussed in the next subsection, was discussed in [59] and is recalled here.

5.3.1 Modeling approach

To detect conflict situations, a modeling approach was developed within the research project MODIS and published in Pascucci et al. [59]. The idea behind this is that a road user, called *Ego User* or *EU*, has to assess if the presence of another user in proximity, called *Competitive User* or *CU*, represents a conflict situation. This is modeled by assuming a field of vision of radius r and angle α (Fig. 5.6), which reflects the extent of human perception.

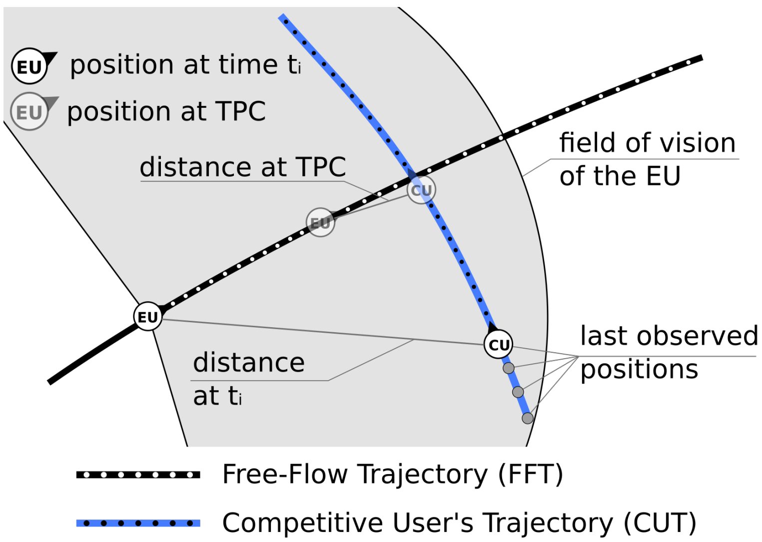


Fig. 5.6. Conflict detection: estimation of relative distance between *EU* and *CU*

When a *CU* enters this field of vision, the *EU* makes an estimation of his expected behavior, defined in space and time, within a temporal horizon th. This operation is executed at a given time step t_i by extrapolating the last four observed positions of the *CU* (from t_i to t_{i-3}) and by applying a Lagrangian polynomial. Successively, the mean value of speed (observed in the same time interval) is used to add the temporal information to the spatial trajectory.

The result is a collection of points *P* (x;y;ts), here called *Competitive User's Trajectory* (*CUT*, blue color), which reflects the estimation of the expected behavior of the *CU* operated by the other users around, *EU* included.

In order to determine whether the situation at time t_i represents a conflict, the SST of the Competitive User is compared with the *FFT* of the Ego User. The focus is on the relative distance between future positions at time $i+j$ (with $j \geq 0$), which is estimated by computing a distance function fun^d according to Eq.(5.1)

$$fun^d(t_{i+j}) = dist[FFT(t_{i+j}), CUT(t_{i+j})] \tag{5.1}$$

As a result, we can expect fun^d to be approximately as in Fig. 5.7. Therefore, a conflict is detected as soon as the value of fun^d gets lower than a certain threshold, called *safety distance* (SD). This reflects the idea that a conflict exist not only when the users would collide ($SD \leq 0$) but also when a sort of respect zone is crossed: Users indeed want not only to avoid conflict, but also to keep away from them. The temporal distance to the time when DF is lower than SD for the first time is called *Time to Possible Collision* (*TPC*).

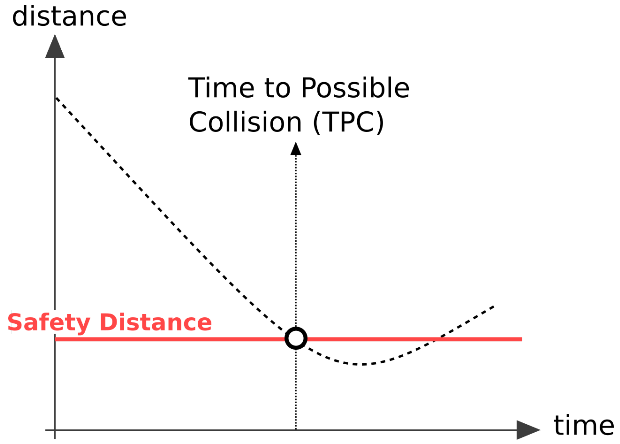


Fig. 5.7. Conflict detection: exemplary distance function fun^d and identification of Time to Possible Collision (*TPC*)

The developed conflict detection algorithm uses information only from the point of view of the *EU*, who compares his *FFT*, which he only knows, with the *CUT* of the *CU*, which is estimated by observation and can diverge from the effective *FFT*. In this way, this modeling approach makes it possible for users in the simulation to misinterpret some situations, which is a quite realistic possibility.

The conflict detection layer returns, for every pair of users in the simulation, the binary variable Y/N if a conflict exists. Moreover, the specification of the time (*TPC*) is returned, which is necessary for the decisional layer.

5.4 Conflict decision layer

The conflict decision layer acts like a filter between the stimulus, detected in the conflict detection layer, and the reaction, to be performed in the conflict reaction layer. Here, it is first decided whether a long-range reaction has to be performed at all, which is based on the value of the *TPC*. Successively, if such a reaction is needed, the type is chosen based on the characteristics of the conflict and the conflicting users.

The *TPC* is used as the only reference criterion to decide whether a long-range reaction can be performed. The reason is explained in the following points:

- if the possible collision is too far in the future, usually no reaction is performed. The reason is that performing a behavioral change in advance, e.g., decelerating, may result in a useless loss of time and energy and it should be possibly postponed until not strictly necessary.

- if the possible collision is too close in the future, it usually means one of two things: either the conflict is in the exit stage (it has already been solved and no reaction is needed) or that road users have noticed each other too late and has to react instinctively (a short-range reaction is needed). In both cases, there is, respectively, no necessity or time to perform a long-range strategy.

In these two cases, a long-range reaction is not performed. For possible collisions too far away in the future, a reaction is not needed at all, while for imminent ones, the classical *SFM*, which is short-range, is already providing a reaction, which is sharp and sudden. In light of this, two temporal thresholds are used to classify the *TPC*, namely, t_{SR} (short-range) and t_{LR} (long-range) (see Fig. 5.8). In the remaining zone in the middle, the road user must employ a strategy for conflict solving.

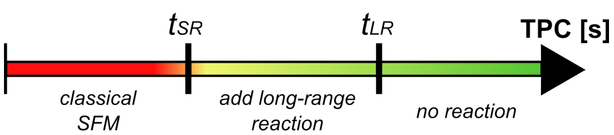


Fig. 5.8. Time to possible collision (*TPC*): temporal thresholds

Summarizing, for *TPC* between t_{SR} and t_{LR}, a choice model was developed to decide which strategy has to be performed to solve any given conflict. The necessity to define standard strategies is due to the high number of possible behaviors, which could be performed, and which may imply the variation of speed as well as direction. Moreover, it has to be investigated what lead road users to choose a certain strategy instead of one another. In this dissertation, we restricted the number of strategies, according to Tab. 5.2.

EU	CU	Strategy	Abbrev.	Change direction	Change speed
Ped	Ped	deviate right	DevR	✓	✗
		deviate left	DevL	✓	✗
Ped	Veh	react prudently	Prud	✓	✓
		react aggressively	Agg	✓	✗
		do not react	PNoR	✗	✗
Veh	Ped	decelerate	DecP	✗	✓
		do not react	VNoR	✗	✗
Veh	Veh	decelerate	DecV	✗	✓

Tab. 5.2. Conflict-solving strategies

Conflict between two pedestrians is usually solved by deviating without modifying the walking pace. In fact, decelerating is perceived as less comfortable than deviating, i,.e., it requires more energy loss. The choice is only related to the turning direction, i.e., left or right. This interaction mechanism and the proposed modeling approach are discussed in Sec. 5.4.1.

When a pedestrian encounters a vehicle, the number of possible conflict strategies is high. The reason is not only due to the high freedom of movement of the pedestrian but also to the chosen trade-off between safety and comfort. The possibility to be injured in a possible collision indeed would make the pedestrian wait for the car to pass, making higher efforts to decelerate or eventually to stop. On the other hand, the pedestrian can also opt for assuming the risk and go straight. This part is discussed in Sec. 5.4.2.

Vehicles in shared streets usually react to conflict situations by decelerating. Taking a detour, leaving thereby the middle line of the lane, is usually risky and is possibly avoided. For this reason, motorists usually perform only speed modifications based on deceleration. In addition, accelerating is quite improbable [72]. When the *EU* is a pedestrian, the motorists could also decide not to decelerate, thereby expecting a pedestrian to behave accordingly by giving him/her way. In this case, a choice model is needed to choose between the type of behavior to perform. This interaction mechanism and the proposed modeling approach are explained in Sec. 5.4.2.

When the *EU* is a vehicle, a distinction should be made whether the shared space is configured as an intersection or road section. By road section, conflict situations are expected only with the vehicle ahead in the same lane. In this case, only decelerating is accepted to avoid collision. By intersection, priority rules define which vehicle has to give way. However, this work deals with road sections, and the latter case is not considered.

5.4.1 Mutual Pedestrian-Pedestrian strategies

Conflict situations between two pedestrians were observed in the video data. The most determinant factor to determine the type of evasive action appeared to be the proximity to the potential collision. If it is not imminent, pedestrians tend to deviate smoothly and keep the current walking pace. If it is imminent, collision is probable, and pedestrians are available to decrease the speed or to deviate suddenly. While this last eventuality is covered in the model by the classical *SFM*, the long-range collision avoidance issue needs the specification of strategies. The choice is essentially restricted to two possible cases, i.e., whether to deviate left or right. Moreover, it is assumed that both conflicting pedestrians take part in solving the conflict.

Visual investigation has highlighted that the logic of the choice is related to the temporal proximity of conflict users to the crossing point (XP), which is assumed as the point where future trajectories cross each other, i.e., the trajectories if no reaction is taken. A sketch is provided in Fig. 5.9. Conflicting pedestrians (*EU* and *CU*) would reach XP at different times. Assuming that they are walking at the same speed, *EU* would be in XP at time t_{XP}^{EU}; at the same time, *CU* has not reached it yet. In this case, the relative distance between them is close (yellow segment).

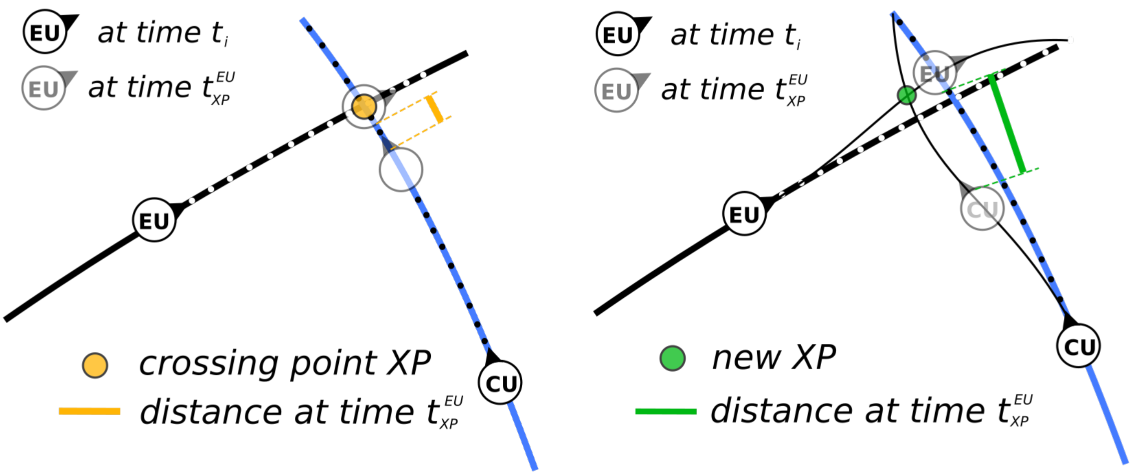


Fig. 5.9. Conflict avoidance strategy between pedestrians: expected relative positions (left), trajectory adjustment (right)

In light of this, a pedestrian adjusts trajectory depending on whether he/she reaches XP first or not. If yes, as the *EU*, the pedestrian crosses the opponent trajectory after XP (in the sketch, *EU* deviates to the left). If not, as the *CU*, pedestrian crosses the opponent trajectory before XP (in the sketch, *CU* deviates to the left). This makes the crossing point shift and, consequently, a higher relative distance to be reached. This mechanism is implemented by comparing the estimated arrival times of *CU* and *EU* in XP [Eq.(5.2)].

$$dir = sign(t_{XP}^{CU} - t_{XP}^{EU}) \tag{5.2}$$

The evasive direction dir is negative when the *EU* reaches XP before the *CU*. In this case, the user deviates in the direction of motion of *CU*. If positive, he goes in the direction of the user. In summary, by comparing arrival times, the direction of the evasive action is established. This modeling approach was developed throughout the project MODIS and has been published in Schiermeyer et al. [70].

5.4.2 Mutual Pedestrian-Vehicle strategies

When a motorist is driving in the circulation zone and a pedestrian is about to cross the street, many possibilities for conflict solving are available. On the one hand, drivers may decide to yield and let the car pass or simply to continue without decelerating. Acceleration is also possible to gain priority over the pedestrian but only to retrieve the desired speed after having decelerated before. Variation of direction (weaving) is usually avoided because it is perceived as unsafe. On the other hand, pedestrians usually perform direction as well as speed modifications. On a general level, different strategies, whether they are for pedestrians or vehicles, can be classified as follows:

Prudent reaction (*PR*) The *EU* performs an evasive action with the purpose to give way to the *CU*;

Aggressive reaction (*AG*) The *EU* wants to take priority over the *CU* and behaves accordingly to make the *CU* his intentions clear;

No Reaction (*NR*) The *EU* does not modify his behavior and continues undisturbed because he would take priority, or give way, even without the need to perform a reaction.

This classification considers the intention of the *EU* with respect to the *CU*, without regarding the specific spatial and speed behavior performed. In fact, making distinctions between the specific way a strategy is performed, i.e., change in direction (left or right) and (-or) speed (accelerate or decelerate), would result in too many cases which makes the model complicated. The above-mentioned strategies are sketched in Fig. 5.10 both for the pedestrian as the *EU* and successively for the vehicle as *EU*. In both images, the dashed lines represent the estimated *CUT* .

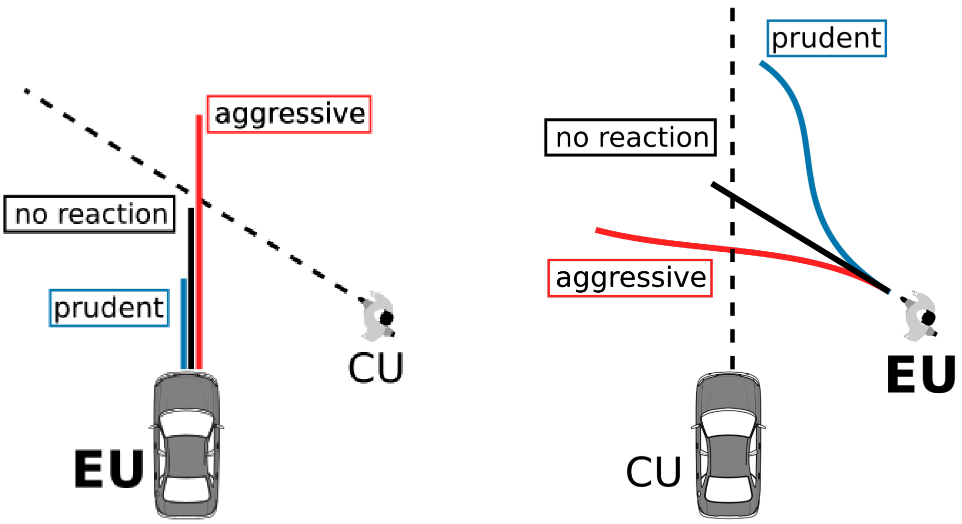


Fig. 5.10. Conflict-solving strategies between one pedestrian and one car: vehicle as *EU* (a, left) and pedestrian as *EU* (b, right)

In this model, it is assumed that drivers perform only speed modifications. Therefore, prudent reaction (*PR*) corresponds to deceleration, while aggressive reaction (*AG*) corresponds to acceleration. Instead, pedestrians can also react by directional changes. Prudent reaction (*PR*) means that the pedestrian does not overstep the border of the circulation zone: If he is walking perpendicularly to it, he/she will decelerate; otherwise, if the *FFT* is oblique, the pedestrian will deviate parallel to the road axis (and smoothly decelerate also). Aggressive reaction (AG) corresponds to cross the road perpendicularly. This allows the pedestrian to hasten the crossing in order to gain priority in advance.

Once strategies are defined, the criterion to prefer a strategy instead of the other has to be investigated. By observation of conflict scenes in the video data, three main classes of factors were assumed to be potentially influential in the choice of the strategy:

- *movement-specific*, e.g., relative position, speed and acceleration of both road users;
- *projected collision-specific*, which describe the expected situation if no evasive action is taken by any of the users;
- *external conflict-specific*, related to the presence of other simultaneous situations of conflict.

Other parameters, e.g., age, gender and time pressure, which may also affect the behavior, were not considered here due to the difficulty to be captured in real-world traffic situations.

In addition, no parameter describing the road layout or regulation is included, because a single scenario was used.

A multinomial logit is chosen to model the process of strategy choice. This modeling approach was selected because of the categorical structure of the response, which includes only three discrete alternatives. Assuming the *NR* strategy as the baseline strategy J, both for pedestrians and vehicles, the multinomial logit assumes the log-odds of each alternative response j to be linearly distributed with intercept α_k and a vector of regression coefficients β_k [see Eq.(5.3)]. The model allows the estimation of the probability μ_j to perform the evasive action j (i.e., *PR* or *AG*) given a set of explanatory variables X:

$$ln(\mu_j/\mu_J) = \alpha_k + X\ \beta_k \tag{5.3}$$

Despite some variables owning a quadratic or cubic relationship with the response, a linear one was chosen with the purpose to keep the model as simple as possible. The substitution of μ_j in the log-odd is called logit transformation and has two benefits in comparison of considering only μ_j: first, it removes ceiling restrictions, i.e., it allows values bigger than 1; second, it removes floor restrictions, i.e., negative values can be considered [Eq.(5.4)].

$$logit(\mu_j) = ln(\mu_j/\mu_J) \tag{5.4}$$

The inverse transformation is called *antilogit* and allows the direct estimation of the probability μ_j [Eq.(5.5)]:

$$\mu_j = logit^{-1}(X\beta_k) = \mu_J\ exp(X\ \beta_k) \tag{5.5}$$

which resides between the range (0,1) for every vector X of the predictors. By determining the probability for strategies *PR* and *AG*, as well as the baseline strategy *NR*, it can be determined which one has the highest probability to be performed.

The definition of the set of predictors X and the estimation of α_k and β_k is performed in Chap.6. This includes the phase of data processing to obtain the dataset of predictors and response, along with the model calibration, to detect only relevant factors and estimate the coefficients. Thanks to this model, it will be determined at every time step whether a reaction has to be performed; if yes, if it should be prudent or aggressive. In this circumstance, the conflict reaction layer will compute the intensity of the reaction to be performed.

5.5 Conflict reaction

The mathematical formulation of long-range forces for every type of conflict, which was part of the research project MODIS, is provided in this section. An overview of the forces is given in Tab. 5.3, with the specification of the related strategy, which was discussed in the previous section. Conflict between two pedestrians is solved by computing the force $\vec{f}_{PP}$. The developed approach, which was published in Schiermeyer et al. [70], is recalled in Sec. 5.5.1. Conflict of pedestrians with a vehicle is explained in Sec. 5.5.2 and includes both the $\vec{f}_{P,PR}$ force, for prudent reaction strategy, and the $\vec{f}_{P,AG}$ for aggressive reaction strategy. The prudent reaction force was part of Rinke et al. [67]. The long-rage vehicle force $\vec{f}_V$, whether the conflict is with a pedestrian or another vehicle ahead, is discussed in Sec. 5.5.3 and was also treated in Pascucci et al. [59].

Note that the aggressive behavior of a vehicle is not considered here; further the *AG* strategy does not have any corresponding acceleration force. The reason is that, even without adding any acceleration force, the vehicle would accelerate anyway because of the formulation driving term. This allows motorists to resume the desired speed, if, at the current time step, the value of speed is lower.

Following the conceptual framework in Fig. 5.4, the step of conflict reaction includes the computation of the intensity of the long-range force. Successively, the contribution is added to the *SFM* equation for the final calculation of new road users' position.

EU	CU	Strategy	Long-range force
Ped	Ped	DevR, DevL	$\vec{f}_{PP}$
Ped	Veh	PedPR PedAG	$\vec{f}_{P,PR}$ $\vec{f}_{P,AG}$
Veh	Ped	VehPR	$\vec{f}_{VP}$
Veh	Veh	DecV	$\vec{f}_{VV}$

Tab. 5.3. Overview of long-range forces with specification of the corresponding conflict solving strategies

5.5.1 Pedestrian reaction vs. pedestrian

The directional change in conflicts involving two pedestrians is reproduced by the social force $\vec{f}_{PP}$. To understand this mechanism, a sketch is provided in Fig. 5.11.

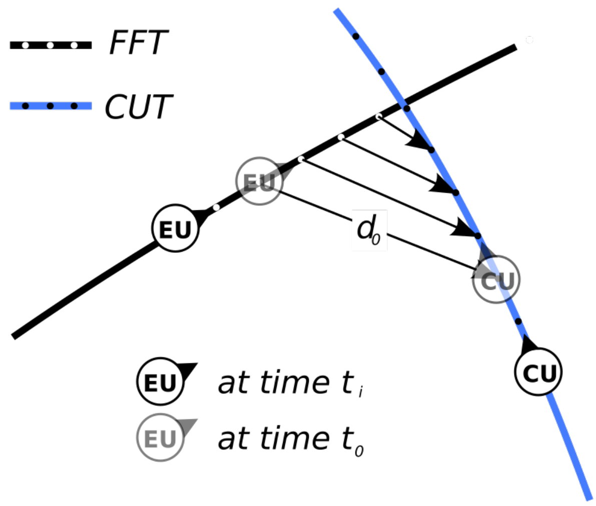


Fig. 5.11. Computation of $\vec{D}(t)$ in conflicts between two pedestrians

The distance $d(t)$ between the road users at any future time t is calculated as in Eq.(5.6) by considering the Free-Flow Trajectory (*FFT*) of the *EU* and the Competitive User's Trajectory (*CUT*) of the *CU*:

$$d(t) = |\vec{D}(t)| = |F\vec{F}T_{EU}(t) - C\vec{U}T_{CU}(t)| \tag{5.6}$$

The reaction force $\vec{f}_{PP}$ is then computed as in Eq.(5.7) by integrating the distance vector $\vec{D}(t)$ using a weight function $w(t)$ incorporating the evasion direction dir [see Eq.(5.2)]:

$$\vec{f}_{PP}(t) = dir \cdot \int_{t_0}^{t_{XP}^{EU}} w(t) \cdot \vec{D}(t)\mathrm{d}t, \tag{5.7}$$

with the arrival time t_{XP}^{EU} of the ego user at the crossing point as the upper and t_0 as the lower bound. The starting time t_0 for the reaction is defined as the time when the distance between trajectories first falls below a given threshold d_0. A weight function $w(t)$ is introduced to balance both the uncertainty of estimated future positions and the influence of the users in proximity. It can be adjusted by two parameters, with k_1 influencing the overall magnitude of the reaction and k_2 describing the shape of $w(t)$:

$$w(t) = k_1 \cdot \left(1 - \left(\frac{d(t)}{d_0}\right)^{k_2}\right) \tag{5.8}$$

Because modifications of walking pace is unusual in conflicts between pedestrians, only the part of $\vec{f}_{PP}$ perpendicular to the direction of movement is used.

5.5.2 Pedestrian reaction vs. vehicle

As discussed in Sec. 5.4.2, two types of reaction are modeled in pedestrian conflicts against a vehicle: The first consists of deviating parallel to the arriving vehicle to give it way (strategy *PedPR*); the second is to deviate perpendicular to anticipate the vehicle and hasten the crossing (strategy *PedAG*). These behaviors are reproduced by adding to the classical *SFM* the forces $\vec{f}_{P,PR}$ or $\vec{f}_{P,AG}$, which are directed, respectively, parallel and perpendicular to the expected trajectory of the arriving vehicle.

The computation of the intensity of forces is performed by the same approach. First at all, the Immediate Stop Force $\vec{f}_{IS}$ is computed, which consist on the force needed to make the pedestrian stop instantaneously (see Fig. 5.12). With reference to the expected *CUT* of the vehicle (dashed line), this force can be divided into two components, namely, $\vec{f}_{IS}^{\perp}$ and $\vec{f}_{IS}^{\parallel}$, which would cancel out respectively the perpendicular and parallel component of motion.

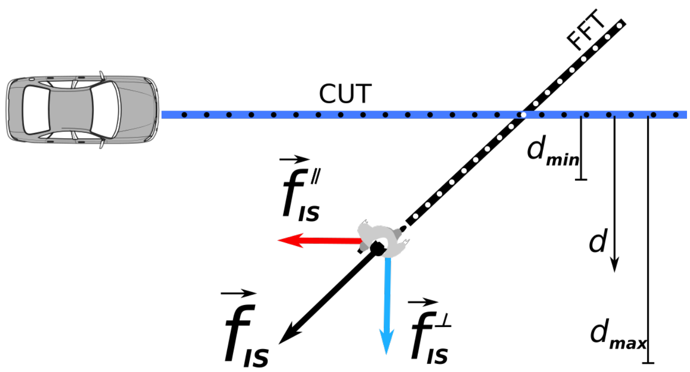


Fig. 5.12. Immediate stop force $\vec{f}_{IS}$ and vector components

When a prudent reaction is taken, the intensity of the deviation and (-or) deceleration is reasonably proportional to the distance to the vehicle *CUT*. This principle is implemented in the formulation of $\vec{f}_{P,PR}$ by including the distance d, computed perpendicularly to vehicle *CUT*. [Eq.(5.7)].

$$\vec{f}_{P,PR}(t) = \begin{cases} \vec{f}_{IS}^{\perp}(t), & \text{if } d(t) \leq d_{min} \\ \vec{f}_{IS}^{\perp}(t) \cdot \frac{d_{min}}{d(t)}, & \text{if } d_{min} < d(t) \leq d_{max} \\ 0, & \text{if } d(t) > d_{max} \end{cases} \tag{5.9}$$

The reaction force corresponds entirely to $\vec{f}_{IS}^{\perp}$ if the distance is minor or equal to a minimum threshold distance d_{min}. For further distances, the value is scaled until a maximum threshold distance d_{max} is reached, where the value is not computed.

The principle behind the computation of $\vec{f}_{P,AG}$ is the following: in the next time step, the speed vector of the pedestrian must be directed perpendicular to vehicle *CUT*; that means, the pedestrian should deviate instantaneously to cross the street. This behavior is implemented by considering the force $\vec{f}^{\,\|}_{IS}$ independently from the relative position of the user to the *CUT*:

$$\vec{f}_{P,AG}(t) = \vec{f}^{\,\|}_{IS}(t) \tag{5.10}$$

5.5.3 Vehicle reaction vs. pedestrian or vehicle

The deceleration of vehicles is implemented by adding a force term $\vec{f}_V$ against the direction of motion. The modeling approach is equal for conflict against pedestrians (VehPR strategy), and by a conflict against another vehicle (strategy *DecV*). The idea behind this is to calculate a lower value of driving speed v^{opt}, which would make the vehicle avoid the collision and, successively, to compute the breaking force $\vec{f}_V(t)$ as in Eq.(5.11), which reflects the formulation of the driving term in the *SFM*:

$$\vec{f}_V(t) = \frac{v^{opt}(t) \cdot \vec{e}^{\,0}(t) - \vec{v}(t)}{\tau} \tag{5.11}$$

In the equation, τ corresponds the reaction time, while $\vec{v}^{\,i}(t)$ is the actual velocity of the vehicle at time t. The value of v^{opt} is determined by the optimal velocity (*OV*) model of traffic flow, proposed by Bando et al. [12]. The basic principle is that a motorist adapts his speed behavior depending on the distance to the conflict point $d(t)$ [Eq.(5.12)]:

$$v_i^{opt}(t) = v_i^D \cdot k[d(t), S] = v_i^D \cdot \frac{tanh(\frac{d(t)}{S} - 2) + tanh(2)}{1 + tanh(2)} \tag{5.12}$$

where v_i^D is the desired speed under free traffic conditions. The term $k[d(t), S]$ ranges from 0 to 1 and is plotted in Fig. 5.13 for different values of the shape parameter S. As is clear from the figure, for the same value of d, the value of k reduces as S increases. In other words, by higher values of S, the optimal speed v^{opt} decreases, and the vehicle decelerates more powerfully.

Depending on the type of conflicting road user, one value of S is chosen, i.e., S_{VP} for pedestrians and S_{VV} for vehicles. In particular, the first one will be calibrated in Sec. 6.2.

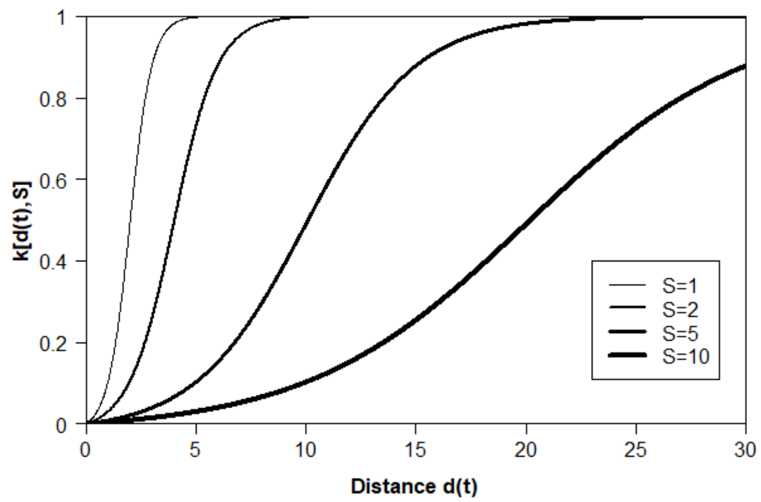


Fig. 5.13. Optimum velocity function for increasing values of S

5.5.4 Multiple conflicts

Until here, the presented forces for conflict solving have addressed single-conflict situations, i.e., where only two road users were involved: one *EU* and one *CU*. However, multiple conflict situations are quite common in shared spaces, especially when traffic volumes increase, and represent a non-negligible part of interaction.

Detecting standard tendencies in behavior is challenging. The reason is that, as the number of simultaneous conflicts increases, the combinations of different types of conflicting road users grow exponentially. Moreover, considering the spatial factor (i.e., different spatial configurations of the conflict), the availability of video material must be huge in order to provide evidence of a standard behavioral pattern. Given the limited resources of this work, in term of time and data availability, a systematic analysis of behavioral patterns was not performed. Nevertheless, basic principles of multiple conflict dynamics have been implemented based on observed tendencies, which are exposed as follows.

1. When a motorist encounters many pedestrians (*EU*=vehicle and *CUs*=pedestrians) who want to cross the road, the tendency to yield increases. This is due to the multiple threats of collision, which makes the motorist more prudent.

2. For the same reason, a pedestrian tends to behave more prudently if he/she encounters many vehicles (*EU*=pedestrian and *CUs*=vehicles).

3. In multiple conflicts among pedestrians (*EU*=pedestrian and *CUs*=pedestrians), long-range strategies tend to be nullified. When density is high, and conflicting pedestrians come from different directions, the tendency is to concentrate on a short-range because the development of the situation appears to be too uncertain. This fact is confirmed by

good performances of the social force model when applied to high-pedestrian-density environments, where forces are only short-range.

In light of this, it was chosen to consider these principles by adapting the developed model to the case of multiple conflicts instead of building new modeling mechanisms. To account for Principles 1 and 2, the conflict decision layer for mutual pedestrian-vehicle conflicts (Sec. 5.4.2) was adapted. This part is discussed in Sec. 5.5.4. To account for Principle 3, the long-range mechanism between pedestrians (Sec. 5.4.1) was switched off when more than one conflict against pedestrians was found. Finally, in the case of mixed CU, namely pedestrian(s) and vehicle(s) together, only the temporally closest conflict was chosen, independently from the type of *EU*. However, despite these mechanisms having basic approximation and can certainly be improved, they are simple and straightforward. Future research should focus on classifying multiple conflict situations, finding common behavioral patterns and identifying conflict-solving strategies, as it was done for single conflicts.

Same type of CUs

The developed approach for mutual vehicle-pedestrian conflict was extended to include the eventuality of many *CUs* of the same type. This issue was published in Schiermeyer at al. [71]. Assuming the *EU* has many conflict situations at time t, probabilities are computed for all strategies (*NR*, *PR*, *AG*) and with respect to all conflicting users. This results in a set of probabilities μ_j^k, where j denotes the possible strategy and k the conflicting CU among the total n. An exemplary situation is sketched in Fig. 5.14, which shows a pedestrian in conflict with two vehicles ($n = 2$).

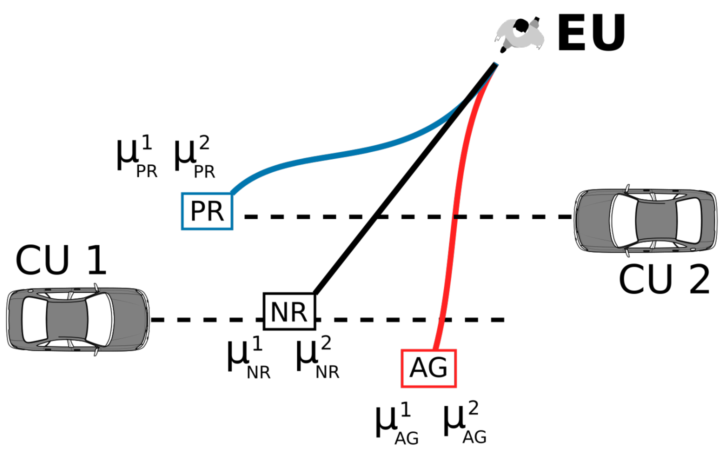


Fig. 5.14. Computation of probabilities for strategy choice in multiple conflicts

Single probabilities are aggregated by the *linear pooling* as proposed by Stone [75]:

$$\mu_j^G = \sum_{k=1}^{m} w_k \mu_j^k, \tag{5.13}$$

where the aggregated probability μ_j^G is expressed as a convex combination of the single probabilities. In the present work, equal weights w_i are used for all probabilities. Despite this, different weights depending on conflict characteristics, e.g., the value of *TPC*, can be assigned.

As global probabilities are computed for each strategy, it has to be decided which one to chose. For single conflicts, this issue was solved by simply choosing the highest probability. Nevertheless, as explained before, in multiple conflicts, road users show a higher tendency to choose the safest available strategy. Therefore, it can be assumed that the likeliness to behave prudently (strategy *PR*) increases as the number of conflicting road users increases. To incorporate this effect in the model, a threshold function $T(n)$ is introduced as:

$$T(n) = \frac{k_1}{n^{k_2}}, \tag{5.14}$$

where m is the number of interacting users, k_1 is the initial threshold for $T(n=1)$ and k_2 is a shape parameter describing the decrease of the function. Fig. 5.15 shows the influence of the shape parameter and the number of simultaneous conflicts in the threshold function.

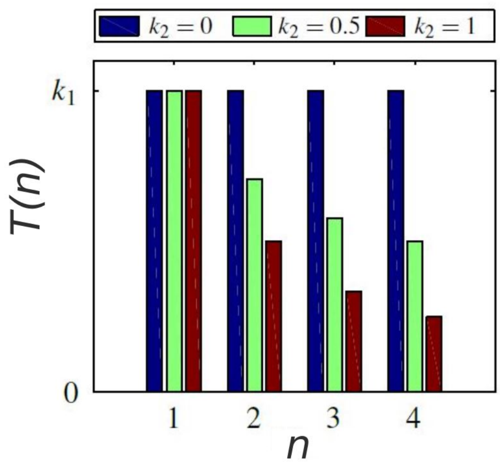


Fig. 5.15. Threshold values in multiple conflicts, from Schiermeyer et al. [71]

After the global probabilities μ_j^G are calculated, the probability for the prudent reaction is compared to the respective threshold value T. If the probability for the prudent reaction is higher than the threshold value, the prudent reaction is chosen in any case. Otherwise, the highest global probability is chosen. Because the threshold function is decreasing for a higher number of interacting road users, the result of this approach is that, as the number of interaction users increases, a higher level of perceived safeness is required for choosing a non-prudent behavior.

Different type of CUs

Competitive users can also consist of a mixture of vehicles and pedestrians. For example, we can think on a crossing pedestrian who has to consider both a vehicle driving in the circulation zone and another pedestrian on the other side of the road. This case was not investigated in this work, and no modeling approach was proposed. Nevertheless, in order to cover this eventuality, it was assumed for the *EU* to only consider the conflict closest in time. Despite this approach being quite realistic when conflicts are distant in time, there is the risk that, when they are close to each other, unrealistic behaviors are performed. This fact was observed in the simulation, especially with high traffic volumes, where multiple conflicts are more likely to occur, and represents a limit of the developed model.

5.6 Implementation in a microsimulation tool

The model has been implemented as part of the simulation software MODIS, which is written in Java. A graphical user interface (GUI), which is shown in Fig. 5.16, was created. This consists of four different elements, which are listed as follows with the respective number in the figure:

1. **Toolbar**: Provides commands to load configuration files, to start/stop the simulation and to save output files. Moreover, it allows us to display model specific patterns, such as the visibility graph or the perception field of all users
2. **Simulation window**: Shows the simulation environment, including the street space and the interaction between users.
3. **Status bar**: Provides the coordinates of the selected point in the simulation area as well as the current position of the cursor.
4. **Control menu**: Allows the visualization of user-specific features for in-simulation analysis.

The process of simulation can be basically divided into four steps, which are listed below and successively discussed:

- Preliminary operations for loading configuration files

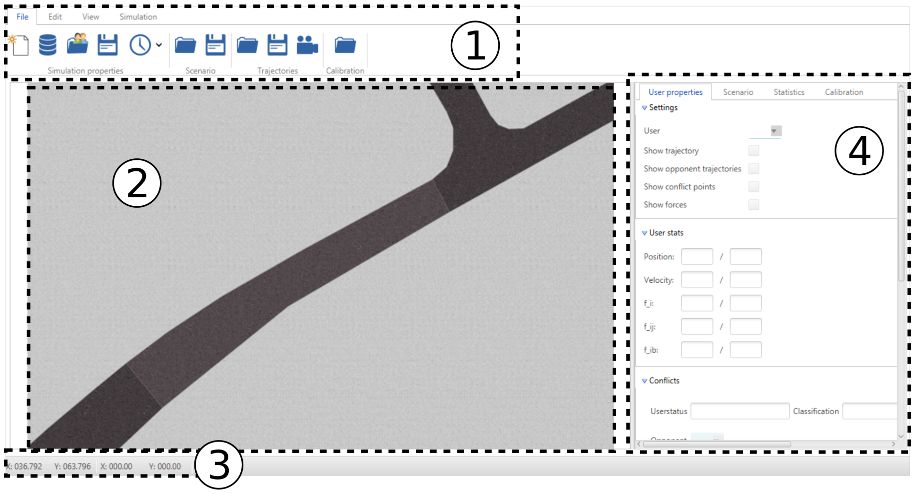


Fig. 5.16. Graphical User Interface of the simulation software MODIS

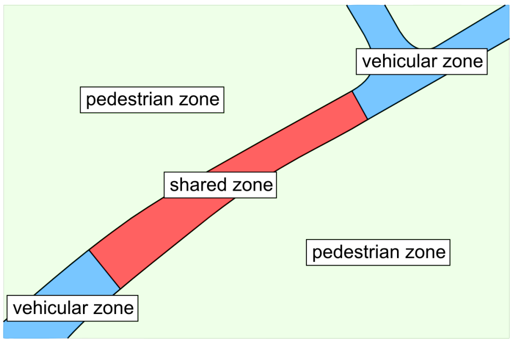
- Simulation run
- In-simulation analysis
- Post-simulation saving of simulation files

The first step consists of loading the files needed for the simulation, i.e., the traffic supply and traffic demand.

The traffic supply is described by a CityGML infrastructure file (with extension *.gml*), which contains information about the traffic space. CityGML [30] is a digital information model to represent urban objects and was integrated with a transportation sub-model, which focuses on geometrical as well as topological aspects of the space. In this way, traffic areas with specific function, as well as declaration about allowed traffic modes, are defined. For the present application, three basic traffic areas were generated: the motor zone, where only motorists are allowed; the pedestrian zone, where only pedestrians are allowed; and the shared zone, where all road users are allowed. The last one corresponds to the "circulation zone" and is the only area where interaction among different types of road users occur. According to this classification, the case study of Bergedorf was divided into traffic areas as shown in Fig. 5.17a, marked by different colors. Moreover, urban objects like curbstones, seats and poles can be defined. Finally, once the *.gml* file is loaded, the software computes the visibility graph with the given geometry and elements.

Traffic demand is specified in an XML-based input file (with extension *.xml*), which includes two main parts: In the first, the position of all destinations points is established, and an identification number is associated. In the second, each road user is defined with attribute specifications, including:

- type of road user (pedestrian or motorist)



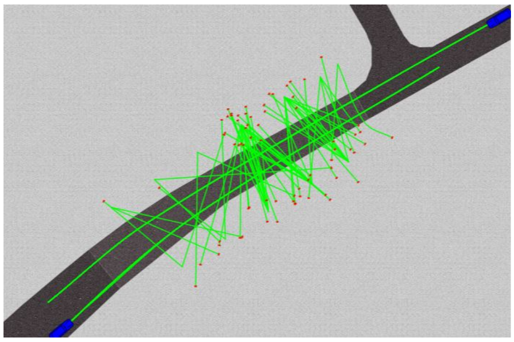


Fig. 5.17. Subdivision in traffic areas (left) and view of the simulation software with the *FFT* of road users (right)

- initial position
- initial speed
- time step to appear in the simulation
- intermediate destinations

As the *.xml* file is loaded, the *FFT* is computed automatically for every road user. These trajectories are immediately displayed (Fig. 5.17b), so that a manual adjustment can be operated.

The simulation can be run both in continuous mode and also by single steps. Moreover, it can be stopped at any time and run backward. The navigation and zooming of the space are possible by dragging and scrolling with the mouse. To test the effectiveness of the model, some features can be visualized by the toolbar, e.g., *FFTs*, visibility graph, and traffic areas.

Instruments for in-simulation analysis are also provided. By stopping the simulation at a given time, statistics of road users can be read in the lateral window, e.g., position, speed, and intensity of the social forces. Visual attributes can be displayed as in Fig. 5.18, where an exemplary conflict situation of a pedestrian (User 1) against a vehicle (User 0) is reproduced: the *FFT* is depicted by the green dotted line, the *CUT* by the blue line, the conflict point by the purple circle, and the current social forces around the pedestrian (in this case: white color for the driving term and black for the prudent reaction force).

Conflict-related features can also be visualized at every time step in the lateral window (Fig. 5.19a). The interface shows that the pedestrian (User 1) is in a conflict situation with the vehicle (User 0), with specifications about the position of the conflict point and the time to possible collision (*TPC*). Moreover, the distance function (as already shown in Fig. 5.7) is provided for a better investigation of the characteristics of the conflict.

The behavior of the road user until the current simulation step can also be displayed in the lateral panel, which provides the distance walked (or driven) and the speed profile over

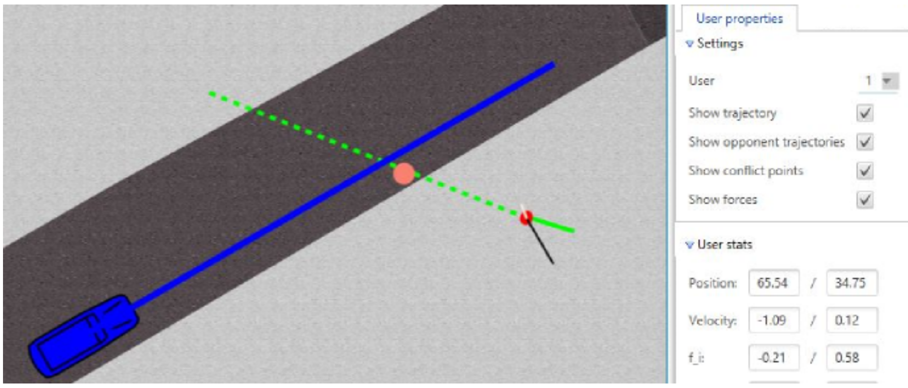


Fig. 5.18. Screenshot of the simulation software: relevant conflict features displayed

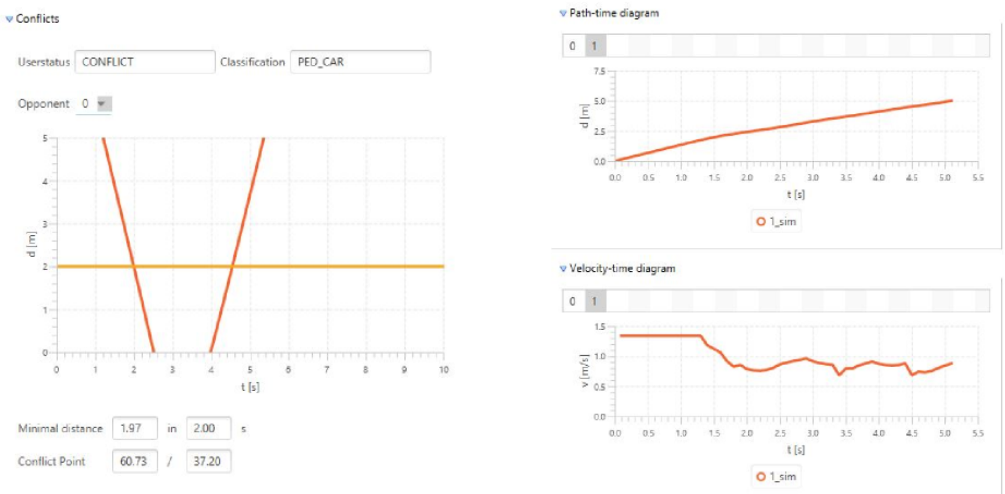


Fig. 5.19. Screenshot of the simulation software: distance function (left) and spatial and speed profiles (right)

time (Fig. 5.19b). In this case, it can be seen how the pedestrian (User 1) has decelerated to let the car pass.

Once the simulation is completed, the software allows us to extract a *.csv* file containing all positions of all road users at every time step. In this way, the results of the simulation can be post-processed externally.

6 Model calibration

Once the modeling approach is developed, model parameters must be adjusted to realistically reproduce road users' behavior and traffic performance characteristics. This process is called "model calibration‘" and is aimed at improving the model‘s ability to accurately represent local traffic conditions and behaviors [25].

The previous chapter dealt with the development of a microsimulation model, which consists of the integration of the classical *SFM* with three layers, i.e., conflict detection, decision, and reaction. This resulted in a large set of parameters, in which any of them could potentially be adjusted to make the model more realistic.

To calibrate the developed model, two approaches are proposed.

Microcalibration This approach assumes real-world situations as the ground truth. Short footage - of the order of seconds - is selected within the available video material according to given criteria, which regard the number and type of interacting users as well as the type of reaction performed. Therefore, the calibration focuses only on the model parameters, which are expected to be relevant in the selected scenes. The calibration method consists of a genetic algorithm and is based on parameter optimization. The advantage is that it is accurate, because, for a given real-world traffic scene, it provides the "best set" of parameters. The drawback, however, is that it requires high availability of data to produce realistic results. In fact, especially when the number of parameters to be calibrated is large, the "best set" can be implausible if the number of selected scenes is low. This calibration approach has been developed within MODIS [70] and is discussed in Sec. 6.2.

Macrocalibration This approach assumes the average value of given *MOEs* within a fixed-time interval as the ground truth. Middle to long video sequences are selected, i.e., of the order of minutes, and the *MOEs* are computed for all types of road users. Successively, the simulation is run by the same time length and the model parameters are adjusted to decrease the deviance between real and simulated values of *MOEs*. On the one hand, the advantage is related to the method‘s straightforwardness, because it simply requires the computation of reference *MOEs* and the choice of the parameters to be adjusted. On the other hand, the drawbacks are related to the inaccuracy of the estimation. In fact, when selecting longer time intervals, all model

Category Name	Subcategory Name	Parameter EU = Pedestrian	Parameter EU = Vehicle
Conflict detection	Field of vision radius	r_p^s	r_v^s
	Field of vision angle	α_p^s	α_v^s
	Reaction time	τ_p	τ_v
	Safety distance	SD_{pp}, SD_{pv}	SD_{vp}, SD_{vv}
Conflict decision: short/long range	Short range time	t_{pp}^{SR}, t_{pv}^{SR}	t_{vp}^{SR}, t_{vv}^{SR}
	Long range time	t_{pp}^{LR}, t_{pv}^{LR}	t_{vp}^{LR}, t_{vv}^{LR}
Conflict decision long-range strategy	Choice model: for every strategy j	$\alpha_{k,p}^j$, $\beta_{k,p}^j$	$\alpha_{k,v}^j$, $\beta_{k,v}^j$
Conflict reaction: short range	Intensity	s_{pp}, s_{pv}	s_{vp}, s_{vv}
	range of influence	r_{pp}, r_{pv}	r_{vp}, r_{vv}
Conflict reaction: long range	CU= pedestrian	d_0, k_1,k_2	S_{vp}
	CU= vehicle	d_{min}, d_{max}	S_{vv}

Tab. 6.1. Parameters of the developed model divided in categories

parameters are potentially influent - interaction between users occur in the most diverse ways. Therefore, given that aggregated indicators are "macroscopical" by nature, it is difficult for the modeler to discern which parameters effectively require adjustment. Since performing a systematic analysis with all model parameters is impossible - combinations grow exponentially - the attention can only be focused on a restricted number of them, while all the others have to be defined a priori. That means the result of the calibration, for a restricted number of parameters, is affected by the pre-estimation of non-calibrated ones. This calibration is discussed in Sec. 6.3.

An overview of model parameters is provided in Tab. 6.1 via categories and subcategories. Moreover, a subdivision is made depending on the type of ego user (*EU*) considered, i.e., pedestrian or vehicle, which is also indicated in the subscript of the parameter, respectively, v and p. When two subscripts are present, the second refers to the competitive user (*CU*). For explanation of single parameters refer to Chap. 5.

Parameters have been divided into categories following the classification *detection-decision-reaction* of a conflict, per the previous chapter. The category *conflict reaction* was divided into short range and long range. For the sake of model calibration, it is important to note that parameters belonging to the short-range category are always involved and also when conflicts are long range (see Fig. 5.4). The category *conflict decision* was split into two parts: the definition of the value of safety distances (SD), and the estimation of the coefficient of the choice model for mutual pedestrian-vehicles conflicts.

The parameter classification according to Tab. 6.1 is fundamental for understanding the micro- and macro-calibration approaches, which concern the calibration of all model parameters except for the category *conflict decision: choice model*. In fact, this model was calibrated apart. The reason is that a deep analysis has to be performed in regard to which predictors play a role in the choice of the strategy, and to what extent. This step is carried out in Sec. 6.1, and it returns a ready-to-use choice model, which can be implemented in the developed modeling framework. That is, by the mentioned calibration approaches (micro and macro), the parameters of the choice model are fixed.

Despite all listed parameters being potentially calibrated by micro and macro approaches, the calibration in this work has involved only three of them, besides those of the choice model. The parameter S_{vp}, which regulates the deceleration of a vehicle that yields to a pedestrian, was submitted to the microcalibration (see Sec. 6.2). This parameter was chosen because single vehicle-pedestrian conflicts, in which the motorists yield to the pedestrian, were actually the most usual case in the available video material. By a large number of these traffic situations, the calibration of S_{vp} (taken singularly and not in combination with other parameters) would have led to realistic results. The parameters r_{vp} and r_{pv}, which regulate the interaction between vehicles and pedestrians (from both sides), were submitted to the macrocalibration (see Sec. 6.3). Despite being related to the short-range interaction, in this modeling approach they are actually involved even for higher spatial ranges. In this sense, they integrate the long-range reaction. The extent to which this integration happens is defined by the parameter r: for this reason, their calibration was considered fundamental. Moreover, the value was found to influence the resulting values of *MOEs*, which is the reference criteria for macrocalibration.

Future research can deal with the calibration of other model parameters, including more of them at the same time. Given the low data availability of this thesis (trajectories were manually tracked), we chose to focus on a restricted number, with the aim to provide a valid application of calibration approaches - besides the theory - and to demonstrate the effectiveness of the methods. For all other parameters, a reasonable value was assumed on the basis of previous literature, logical reasoning and visual analysis in the simulation. The values are provided in Tab. 6.2.

6.1 Decisional model

The choice model for mutual pedestrian-vehicle strategies introduced in Sec. 5.4.2 is calibrated and validated. The objective is first to detect a set of predictors X, which govern the decision of a strategy, for both pedestrians and motorists. Second, to determine the relation between predictors and outcome by calibrating the set of coefficients β_k as well as the intercept β_k for all possible strategies. Finally, to validate the model.

Category name	Parameter	
	EU = pedestrian	EU =vehicle
Conflict detection	$r_p^s = 30$ $\alpha_p^s = 200°$ $\tau_p = 0.5$ $SD_{pp} = 0.3$ $SD_{pv} = 2$	$r_v^s = 30$ $\alpha_v^s = 200°$ $\tau_v = 2.4$ $SD_{vp} = 2$ $SD_{vv} = 3$
Conflict decision: short/long range	$t_{pp}^{SR} = 1$ $t_{pv}^{SR} = 1$ $t_{pp}^{LR} = 2.5$ $t_{pv}^{LR} = 5$	$t_{vp}^{SR} = 1$ $t_{vv}^{SR} = 1$ $t_{vp}^{LR} = 5$ $t_{vv}^{LR} = 5$
Conflict decision: long range strategy	$\alpha_{k,p}^j$, $\beta_{k,p}^j$ [Sec. 6.1]	$\alpha_{k,v}^j$, $\beta_{k,v}^j$ [Sec. 6.1]
Conflict reaction: short range	$s_{pp} = 5$ $s_{pv} = 10$ $r_{pp} = 0.4$ r_{pv} [Sec. 6.3]	$s_{vp} = 10$ $s_{vv} = 20$ r_{vp} [Sec. 6.3] $r_{vv} = 0.6$
Conflict reaction: long range	$d_0 = 2$ $k_1 = 3$ $k_2 = 0.5$ $d_{min} = 1$ $d_{max} = 4$	S_{vp} [Sec. 6.2] $S_{vv} = 20$

Tab. 6.2. Parameters of the developed model:
assumed values and parameters submitted to calibration

Conflict situations were detecting by analyzing tracked trajectories among themselves through a three-step methodology, which is performed at every time step ts^*. First, the expected behavior of road users was predicted by collecting the last four observed points of every road user and by fitting a cubic smoothed spline, which can estimate the expected position in the following 8 s. Second, predicted positions are compared with each other to calculate the future relative minimum distance (*MinDist*) among road users. Third, the current ts^* - with the information of road user's ID - is saved as conflict instant (*CI*) when this distance is found to be below 5 m. This resulted in a set of 2814 *CIs*, belonging to 409 different conflict situations involving one vehicle and one pedestrian.

Successively, the predictors listed in Tab. 6.3 were computed for every *CI*.

Predictor	Type	Unit [1]	Description
MinDist	cont	m	minimum expected relative distance of road users
TimeMinDist	cont	m	temporal proximity to the situation of MinDist
ActDist	cont	m	distance at time step ts^* between road users
OrtDist	cont	m	distance at time step ts^* between the pedestrian and the expected trajectory of the vehicle
TimeDelayXP	cont	s	temporal delay of the pedestrian - with respect to the vehicle - to reach XP (point where trajectories cross)[2]
SpeedVeh	cont	m/s	speed of the vehicle at ts^*
AccVeh	cont	m/s^2	acceleration of the vehicle at ts^*
SpeedPed	cont	m/s	speed of the pedestrian at ts^*
AccPed	cont	m/s^2	acceleration of the pedestrian at ts^*
CPConfNr	dis	n°	number of simultaneous conflict of a vehicle against pedestrians
PCConfNr	dis	n°	number of simultaneous conflict of a pedestrian against vehicles
CarAhead	dis	Y/N	if the driver has another vehicle behind

[1] *cont = continuous, dis = discrete*
[2] *negative if the vehicle would anticipate the pedestrian*

Tab. 6.3. Set of explanatory variables considered

Finally, it is determined how road users reacted to conflicts, i.e., which nominal outcome must be associated to every *CI*. For this purpose, the critical element is represented by the delay between the moment ts^*, where the conflict was observed, and the moment when the road user reacted accordingly. This temporal delay between stimulus and reaction is assumed here as 1.5 s, which includes the *perception time* (needed to perceive the stimulus), the *decision time* (needed to elaborate a conflict solving decision), and *reaction time* (needed to react physically). Consequently, while the values of the predictors are calculated at time ts^*, the reaction choice is detected at time $ts^* + 3ts$ - i.e., 1.5 seconds later. The type of evasive action is identified through a five-step method, which is briefly described here and shown in Fig. 6.1b for the pedestrian case (and applies similarly to vehicles):

- The *expected trajectory* of the pedestrian is computed by a cubic smoothing spline through the last three observed positions and the actual one $[P_{ts^*-3}; P_{ts^*}]$;
- The *observed trajectory* of the pedestrian is computed by a cubic smoothing spline though the future three observed positions and the actual one $[P_{ts^*}; P_{ts^*+3}]$;
- The intersections between the *expected* and the *observed trajectory* with the *vehicle trajectory* are saved, respectively, as XP_{Exp} and XP_{Obs};
- The time needed by the pedestrian to reach XP_{Exp} and XP_{Obs} from P_{ts^*} is computed;
- The temporal difference $k(ts^*)$ between XP_{Exp} and XP_{Obs} is used as the reference value to classify the reaction. Negative values of $k(ts^*)$ indicate that the pedestrian has adopted a prudent behavior with the intention to give way to the vehicle.

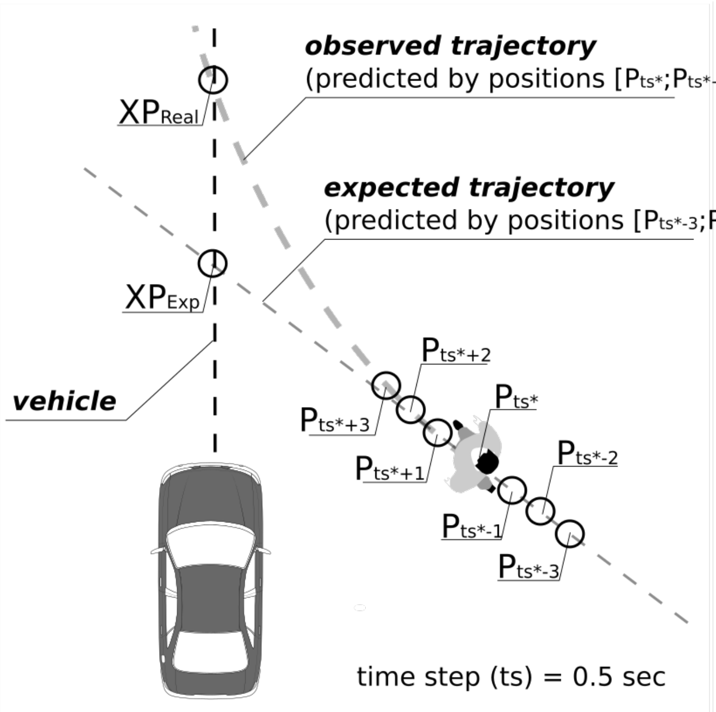


Fig. 6.1. Determination of the strategy: Case between a pedestrian in conflict with a vehicle

The benefit of the statistic $k(ts^*)$ is due to the possibility to quantify the intensity of the evasive action by a single value, without computing any speed or directional change. The statistic $k(ts^*)$ was computed for all *CIs*, both for pedestrians and vehicles. The distribution of the variable is shown in the histograms in Fig. 6.2a for pedestrians and in Fig. 6.2b for vehicles. Given the distribution of the variable $k(ts^*)$, arbitrary threshold values of ± 0.25 s are assumed to determine which evasive action was chosen. In this way, the reaction is classified, and the data set is ready for the model calibration.

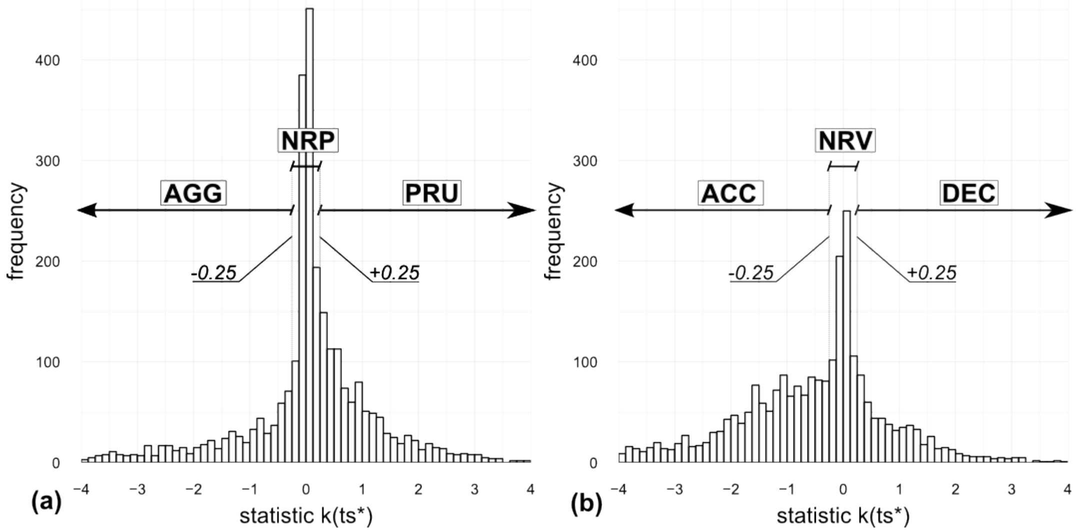


Fig. 6.2. Distribution of statistic k for (a) pedestrians and (b) vehicles and assumed thresholds for determining the reaction

In the first stage, the relation between the predictors and the outcome is tested, with the aim to identify a set of explanatory variables, which are determinant for the choice of evasive action. The analysis is carried out by the maximum likelihood method: further, the statistical significance of each predictor is checked by the *Z*-value, which is defined as the regression coefficient divided by its standard error. The significance is checked with a two-sided test under the null hypothesis that the given variable does not affect the outcome. The analysis is performed both for pedestrian and drivers by estimating the coefficients β_k for the model with all predictors (full model).The significance test used here is the *two tailed Z-test*, which assumes the *Z*-value to follow the standard normal distribution. As described in Eq. (6.1), the *Z*-value is defined as the estimate divided for its standard error:

$$Z_i = \frac{\beta_k}{\sigma_i} \tag{6.1}$$

This test highlights which variables are statistically significant and which could be omitted in the model. The results of the regression are shown in Tab. 6.4 for drivers and in Tab. 6.5 for pedestrians (in both cases, one regression is performed for each alternative).

The result of the goodness-of-fit test expressed through the *chi-square* statistic shows that the improvement given by the explanatory variables with respect to the null model is significant. The associated *p*-value (calculated under the null hypothesis that the model fits the data

Variable	No reaction -> Prudent β_k	Std. err.	Z-value	Pr(>|z|)	No reaction -> Aggressive β	Std. err.	Z-value	Pr(>|z|)
MinDist	-0.38	0.06	-6.48	**0.00**	-0.28	0.07	-4.22	**0.00**
TimeMinDist	0.40	0.10	4.07	**0.00**	0.46	0.11	4.33	**0.00**
ActDist	-0.02	0.03	-0.85	0.40	0.05	0.03	1.80	0.07
OrtDist	0.16	0.06	2.55	**0.01**	0.16	0.07	2.28	**0.02**
TimeDelayXP	0.17	0.02	8.36	**0.00**	0.10	0.02	4.20	**0.00**
SpeedVeh	-0.05	0.09	-0.59	0.55	-1.03	0.12	-8.50	**0.00**
AccVeh	-1.70	0.11	-14.88	**0.00**	1.27	0.13	10.07	**0.00**
SpeedPed	-0.18	0.23	-0.79	0.43	0.24	0.27	0.90	0.37
AccPed	0.69	0.28	2.44	**0.01**	-0.92	0.34	-2.72	**0.01**
CPConfNr	0.14	0.05	2.84	**0.00**	0.05	0.06	0.89	0.38
CarAhead	0.58	0.39	1.50	0.13	0.20	0.48	0.42	0.67

Number of observations = 2,838; Dev = 3576.22; Constant-only model: Dev. = 5545.31
Goodness of Fit: chi^2= 1969.09 with d.f.=22. Prob> chi^2 = 1

Tab. 6.4. Vehicle decisional model, full model. Basemodel=No reaction

Variable	No reaction vs Prudent β_k	Std. err.	Z-value	Pr(>|z|)	No reaction vs Aggressive β	Std. err.	Z-value	Pr(>|z|)
MinDist	-0.53	0.06	-8.81	**0.00**	-0.32	0.05	6.04	**0.00**
TimeMinDist	0.54	0.11	5.80	**0.00**	0.62	0.08	7.25	**0.00**
ActDist	0.00	0.09	0.02	0.98	-0.04	0.02	-1.84	0.07
OrtDist	0.30	0.07	4.55	**0.00**	0.07	0.06	1.16	0.25
TimeDelayXP	0.21	0.02	8.64	**0.00**	0.23	0.02	10.02	**0.00**
SpeedVeh	-0.06	0.9	-0.65	0.52	0.21	0.08	2.66	**0.01**
AccVeh	0.32	0.09	3.53	**0.00**	0.12	0.08	1.46	0.15
SpeedPed	-0.53	0.26	-2.05	**0.04**	-2.41	0.23	-10.41	**0.00**
AccPed	-4.01	0.36	-11.13	**0.00**	2.48	0.30	8.39	**0.00**
CPConfNr	-0.08	0.05	-1.52	0.13	-0.01	0.05	-0.30	0.77
CarAhead	-0.30	0.35	-0.87	0.39	0.08	0.29	0.28	0.78
PCConfNr	-0.10	0.10	-1.00	0.32	-0.13	0.09	-1.41	0.16

Number of observations = 2,838; Dev = 4035.30; Constant-only model: Dev. = 6133.63
Goodness of Fit: chi^2= 2098.33 with d.f.=22. Prob> chi^2 = 1

Tab. 6.5. Pedestrian decisional model, all variables. Basemodel=No reaction well) is approximately 1, which suggests that further model specifications, e.g., quadratic relations, are not necessary at the moment. Looking at the *p*-values of single predictors, it can be noticed that only part of them are statistically significant independently from the road user and the chosen reaction, i.e., *MinDist*, *TimeMinDist*, *TimeDelayXP* and *AccPed* (*p*-values are close to 0). The sign also indicates clear tendencies: road users tend to take evasive action when *MinDist* decreases, *TimeMinDist* increases and *TimeDelayXP* increases. That means that road users are more inclined to change their behavior when the moment of minimum closeness is temporarily distant, when it will imply a collision, and when they are ahead of the conflicting user. Moreover, they tend to behave more prudently when they are in a deceleration phase and aggressive when they are accelerating. Other tendencies are user- and reaction-specific, e.g., *CPConfNr*, which is relevant only for drivers when deciding whether to decelerate. For the sake of the model's simplicity, part of the predictors is excluded. The selection was done by excluding variables one at a time and checking for consistent decreases in residual deviance. Relative *chi-square* is respectively, 1943.8 and 2052.7, which is close to the one of the full model.

In order to calibrate and validate the model on different data, the entire sample was split 70% for training and 30% for testing. The coefficient was estimated on the training sample (Tab. 6.6) and successively tested on the validation one, where the likelihood of every reaction choice was computed for all the *CIs*, and the option with the highest probabilities was assumed as the response. The results are shown in the confusion matrix (Tab. 6.7), where each column represents the instances in the predicted class, while each row represents the instances in the observed class.

Vehicle Model			**Pedestrian Model**		
Variable	NR->PR	NR->AG	Variable	NR->PR	NR->AG
Intercept	0.196	-0.309	*Intercept*	-2.193	1.057
MinDist	-0.402	-0.265	*MinDist*	-0.497	-0.309
TimeMinDist	0.365	0.539	*TimeMinDist*	0.745	0.547
OrtDist	0.136	0.225	*TimeDelayXP*	0.288	0.252
TimeDelayXP	0.161	0.116	*SpeedPed*	0.099	-2.344
SpeedVeh	-0.118	-0.800	*AccPed*	-3.919	2.484
AccVeh	-1.738	1.199	*AccVeh*	0.327	0.131
AccPed	0.659	-0.882			

Tab. 6.6. Intercept α and coefficients β estimated by cross-validation

The off-diagonal elements of the confusion matrix reveal in which situations the predicted choice differs from the observed one. The misclassification rate, i.e., the percentage of off-diagonal elements with respect to the total, amounts to 23.1% for drivers and 31.3% for pedestrians. This has to be considered a satisfying result given the high stochasticity of a

	Vehicle Model				Pedestrian Model		
	NR	PR	AG		NR	PR	AG
NR	**125**	57	14	NR	**262**	27	49
PR	22	**420**	22	PR	24	**117**	71
AG	21	55	**92**	AC	54	39	**199**

Tab. 6.7. Confusion matrix: Observed (rows) and predicted (columns) outcome

road user's behavior, which may be strongly affected by parameters like age, sex, or time pressure.

Two exemplifying situations are chosen to show the good performances of the developed model. For each situation, three figures are shown alongside each other: (a) a frame of the video sequence which displays the conflict dynamic, (b) the observed behavior in terms of speed (or direction) with the associated value of the statistic k for every *CI*; (c) the probabilities predicted by the model related to the different reaction choices. For clarity, pedestrian and vehicles are indicated by the letters v and p. Moreover, these abbreviations are capital when the road user's behavior is estimated and tested against observations. In Situation 1 (Fig. 6.3), vehicle $V1$ is in conflict with pedestrian $p1$ (as well the pedestrian next to $p1$). The latter decides to cross the *circulation zone* and forces $V1$ to give way by decelerating. The model predicts the choice correctly for the whole time of conflict, since the *PR* probability is always higher than the alternative ones. In Situation 2 (Fig. 6.4), pedestrian $P2$ (as well as the one next to $P2$) steps onto the roadway with a speed of approximately 0.75 m/s (lower as the desired speed). As vehicle $v2$ decelerates to give him way - and also because there is a vehicle ahead - $P2$ accelerates until it reaches its desired speed (around 1.45 m/s). This behavior is identified as *AG* by the statistic k for the first part of the conflict and is consistent with the outcome of the developed model. Moreover, the transition from *AG* to *NR* is well reproduced.

However, the misclassification rate shows that in approximately 1 *CI* over 4, the model diverges from reality. For this reason - and in view of possible model improvements - many situations were tested, and the reason of model misclassification was annotated. Two main causes were found. The first is related to courtesy behavior, e.g., when a driver decelerates to let a pedestrian cross. In this case, the model would classify the reaction as AG or NR, while the driver actually decelerates (second column of Tab. 6.7 for vehicles). The second is closely related to the heterogeneity of pedestrian behavior. This is evident in Tab. 6.7 for pedestrians, where the AG row and column have a high number of elements. One can think of elderly people who typically prefer to give priority to vehicles even if they could cross safely (elderly people have lower levels of risk acceptance). On the contrary, young people tend to be less prudent and accept higher risks. This case is shown in Fig. 6.5, where the upcoming car $v3$ (which is quite close and fast) is not captured by the video frame. While the observed behavior is classified as AG for the first part of the reaction, the model expects pedestrian $P3$ to be prudent, meaning to let the vehicle pass.

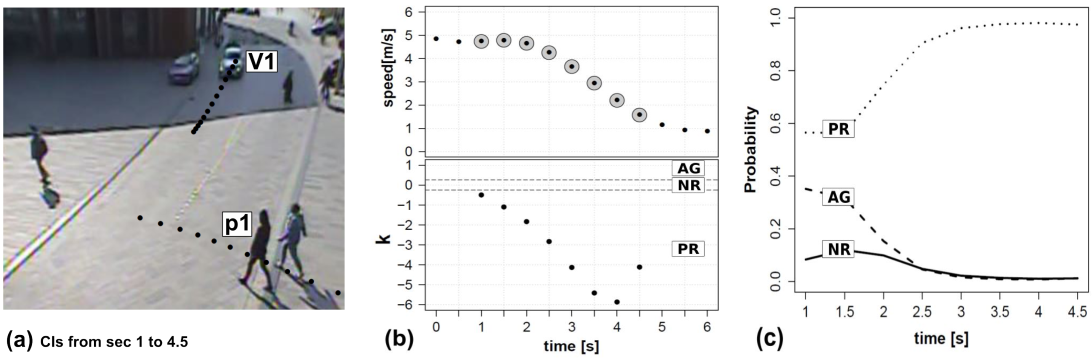


Fig. 6.3. Situation 1: Characteristic values of vehicle V1. The model reproduces the observed behavior.

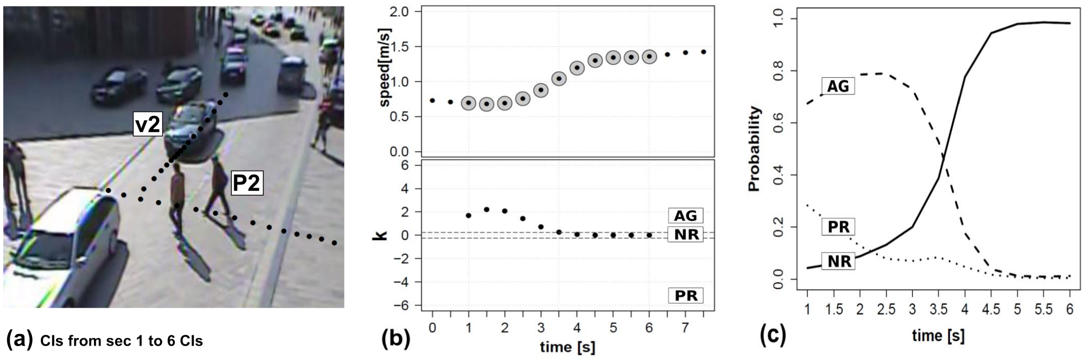


Fig. 6.4. Situation 2: Characteristic values of pedestrian P2. The model reproduces the observed behavior

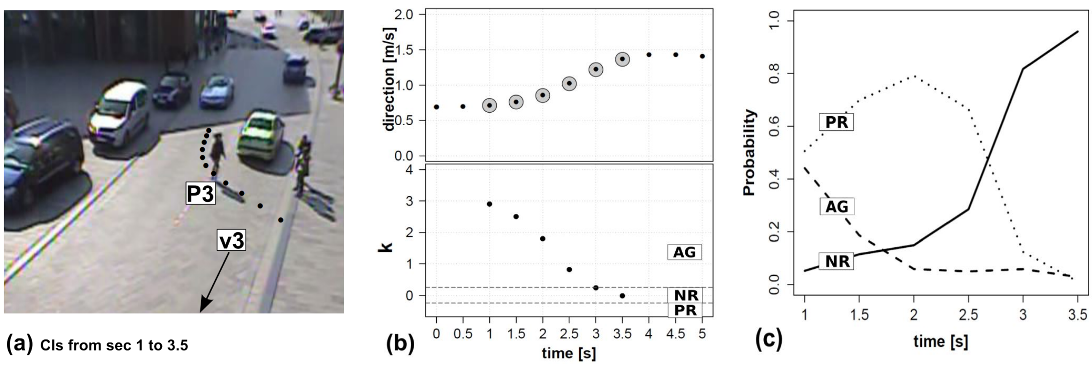


Fig. 6.5. Situation 3: Characteristic values of pedestrian P3. The model expects P3 to be prudent instead of aggressive.

6.2 Microcalibration

This approach considers the trajectories of road users as the reference data for the calibration, which must be specified in space and time. That means, for a number n of interaction situations selected in the video material, the position of all road users at every time step must be given as input. In order to provide meaningful results, the type of interaction situations must be selected according to the chosen parameters to calibrate. Generally, the following steps are required to define a type of interaction situation:

1. definition of the number u of interacting users [$u = 2$ for single conflicts, $u \geq 2$ for multiple conflicts];

2. definition of the type of road users [pedestrians and/or vehicles];

3. definition of the type of reaction [no reaction, short range or long range];

4. definition of the type of strategy [e.g., prudent or aggressive] (only if the reaction is long range and more than one strategy is possible, e.g., by mutual pedestrian-vehicle conflicts).

Once the type of interaction situation is defined, the set of parameters to calibrate can be chosen. For example, when modeling a long-range pedestrian conflict against other pedestrians, one may potentially take SD_{pp}, t_{pp}^{SR}, t_{pp}^{LR} , d_0, k_1 and k_2 altogether - or part of them.

Moreover, the interaction situations must be visually selected within the video material. However, assigning a specific category to a real-world situation can be complicated. Sometimes the influence of "external" road users is difficult to quantify. Moreover, the type of reaction can be difficult to interpret - or it can change over time. For this reason, it is necessary to exclude ambiguous situations because they may negatively affect the results.

Once a set of n real-world scenes is selected, the position of all users at every time step is extracted. These data can be collected in n files with *.csv* extension and constitutes the reference for the calibration. Moreover, for every interaction scene i (for $i = 1, .., n$), a corresponding set of n .xml simulation file is set up. This contains the information about the type of road users involved, initial position and speed and final destination. Once the files are ready, they are submitted to the calibration.

Genetic algorithms (GAs) were originally invented by Goldberg and Holland [29] and apply the natural process of evolution according to the principles of natural selection to optimization problems, i.e., "the survival of the fittest" as stated by Darwin.

Initially, an *encoding scheme* is used to represent a candidate solution, called an *individual*. Starting from a set of candidate solutions (*population*), the algorithm generates an offspring population as long as specific stopping criteria are not satisfied. The generation of an offspring population is based on three genetic operators, i.e., *selection*, *crossover* and *mutation*. The selection operator picks members of the population randomly to create an offspring, favoring fitter individuals. These members generate an offspring via a crossover operator; thereby, each parameter of the offspring's encoding is generated by combining the parameter values of the picked members, e.g., by arithmetic operations or random choice. To retain the diversity of the population among the fitness landscape, the mutation operator randomly modifies the parameter values of the offspring.

The evaluation of a candidate solution is made by a fitness function, which is assumed here as the squared distance between the observed and simulated positions [Eq. (6.2)].

$$f = \frac{\sum_t |\vec{p}_u^{\,obs}(t) - \vec{p}_u^{\,sim}(t)|}{n} \tag{6.2}$$

where $\vec{p}$ represents the position of user u at time t, and n is the number of tracked positions.

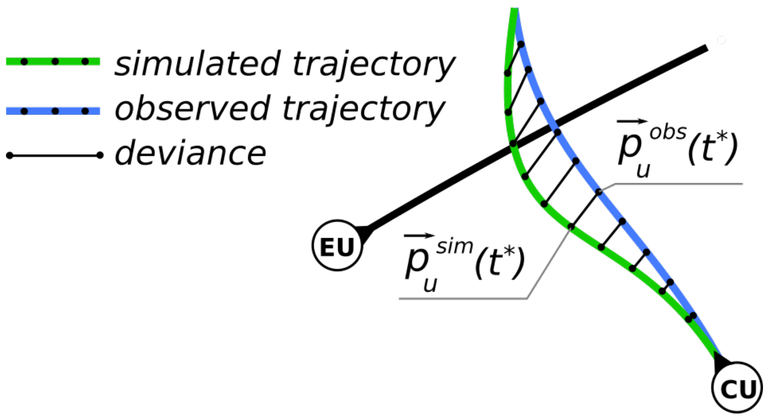


Fig. 6.6. Fitness function: Deviance between observed and simulated trajectory

The calibration is carried out by simulating one user in each conflict scenario, i.e., the *EU* is simulated, while the conflicting user behaves in the simulation according to the observed behavior. As a consequence, every scene results in an optimized set of parameters. In order to obtain a unique set of applicable parameters, an overall fitness function of the GA has been assumed, which consists of the sum of the single fitness of each scenario. This means that, at the end of the procedure, the resulting set will minimize the total deviation of all simulated behaviors to the corresponding observed scenes.

Application

The developed method is applied to calibrate the parameter S_{vp}, which regulates the braking behavior of vehicles in long-range conflicts with pedestrians, and submitted to calibration.

In the video materials, vehicle-pedestrian conflicts were selected according to four conditions, which were defined by following the structure discussed at the beginning of Sec. 6.2: first, only two road users must be involved; second, they must be one pedestrian and one vehicle; third, the vehicle takes a long-range reaction; fourth, the long range reaction consists of a prudent strategy, i.e., deceleration. According to these principles, a total of 35 interaction situations was selected in the video material, and the tracked trajectories were saved as *.csv* files. Moreover, *.xml* files were generated by imposing type of road users involved, origins, destinations, and initial speeds.

Successively, a preliminary selection was performed. The holistic parameter optimization - comprehensive of all scenes together - was first run by assuming 100 as the number of individuals, a maximum of 20 generations, and 0.2 and 0.8, respectively, as recombination and mutation probability. The histogram of fitness values is plotted in Fig. 6.7a. This figure highlights scenes with high fitness function, in which the choice model for vehicles has wrongly predicted the strategy of the *EU*. These situations must be excluded from the data set, because they would lead to erroneous estimation of the parameter. The criterion to be used for excluding them was assumed to be the value of the fitness function. In fact, high fitness corresponds in all likelihood to different strategies adopted by road users with respect to the observed behavior (this was also observed in the simulation). To detect a threshold value of the fitness function as exclusion criteria, the results of the confusion matrix (see Tab. 6.7) are employed to calculate the percentage of wrong estimations when the observed strategy is *PR*, which is 21%. Therefore, the 0.21 quantile of the fitness is calculated (red line in Fig. 6.7a) and all the situations with lower fits were excluded (seven scenes).

Successively, the optimization was performed again on the remaining 27 scenes by the same values of number of individuals, maximum generation, recombination and mutation probability. The resulting fitness values are plotted in the histogram in Fig. 6.7b. The mean fitted values has decreased from -18.4 to -8.3 (-55%). This returned the calibrated value of S_{vp}, which is 26.2.

6.3 Macrocalibration

The objective of this calibration method is to adjust model parameters in order to match reference performance indicators computed in the field measurement. In standard praxis, traffic engineers use road capacity, time delay, queue length, or other performance indicators

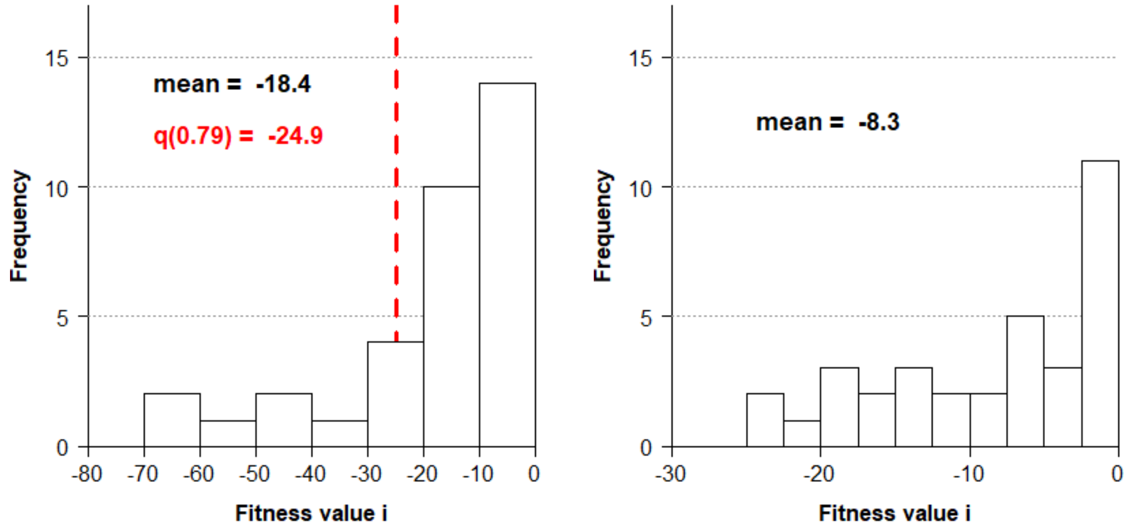


Fig. 6.7. Distribution of the fitness value: Preliminary selection (left), calibration on the selected scenes (right)

as reference for the calibration of simulation models. The focus is usually on a few parameters, whose sensitivity is tested by repeating simulation and by adjusting their values. It is indeed impossible to formulate closed-form equations and to apply mathematical methods to find the optimum values. The reason for this is that simulation models are complex and the number of potentially relevant parameter is high. Therefore, the FHWA recommends "to plot of the output results as points and to searching between these points for the optimal solution" [25]. In this way, the deviance between model estimates and field measurements can be minimized without excessive efforts.

The steps of the developed methodology to perform macrocalibration are listed and discussed here below.

- Selection of the parameters to adjust. It is recommended to focus on parameters that are expected to considerably affect the results. The number of parameters must reasonably be low, since parameter‘s combinations increase exponentially.

- Computation of performance indicators, i.e., vehicle delay (*VD*) and pedestrian comfort (*PC*) in the field measurement. These values are assumed to be the reference for the calibration.

- Definition of simulation settings. While some characteristics of the simulation must reflect the observation field, e.g., traffic volumes, desired speed, O/D matrix, others can be randomized and included in the definition of the random seed, e.g., the temporal gap between road users when they appear in the simulation. By repeating the simulation with different random seeds and by averaging the reference indicators, the specificity of the period of observation on the field can be generalized, and more representative results can be obtained.

- The simulation of the reference scenario is repeated with different sets of values as input parameters, in which each of them resides within a given range. For each set, the simulation is repeated a reasonable number of times with different random seeds. Finally, the reference indicators are averaged.

- By help of error statistics, tables and diagrams, the "best" set of parameters is identified. The ratio is to minimize the error between the reference values from the observation field and the simulated ones. The specific method for identifying the "best" set depends on the number of combinations and parameters selected.

- Identification of a second scenario in the observation field, usually in the off-peak period, to test the goodness of estimated parameters. If the values differ significantly, the procedure of calibration must be repeated by including other parameters.

Application

The feasibility of this method is shown by adjusting parameters r_{pc} and r_{cp}, which describe the extension of the short-range interaction in mutual vehicle-pedestrian conflicts.

The 30-min period of investigation described in Sec. 3 is taken as reference time interval. As calculated in Sec. 4.1.4, the reference performance values of *VD* and *PC* were, respectively, 10.34 s and 0.691. For the simulation, traffic volumes, desired speed, O/D locations and distribution of traffic volumes are taken according to Sec. 3.4. Four aspects were included in the definition of the random seed: First, the headway between vehicles driving in the same lane, which were randomly chosen by the only condition of 2 s as a minimum; Second, the time of appearance of pedestrians in the simulation. Third, pedestrian speed is randomly chosen given a fixed value of mean speed and deviance. Fourth, the point of appearance of each pedestrian was shifted from the centroid of the origin by a random value in the range of 0-3 m in the x and y directions.

The parameters to calibrate were assumed to be in the range of 0.3-0.6. For this reason, four combinations of parameters were tested, each one with five different random seeds. The results of *VD* and *PC* are provided, respectively, in Tabs. 6.8 and 6.9

Parameters		Vehicle Delay by Random Seed..					Vehicle Delay
r_{pv}	r_{vp}	1	2	3	4	5	Mean
0.3	*0.3*	7.95	9.3	6.3	8.86	11.1	**8.70**
0.3	*0.6*	15.14	18.18	15.99	16.68	19.09	**17.02**
0.6	*0.3*	8.05	7.84	6.58	8.48	14.37	**9.06**
0.6	*0.6*	18.79	17.74	12.02	16.47	17.98	**16.60**

Tab. 6.8. Vehicle delay for different combination of parameters.
Simulation with different random seeds and average value.

Parameters		Pedestrian Comfort by Random Seed..					Pedestrian Comfort
r_{pv}	r_{vp}	1	2	3	4	5	Mean
0.3	*0.3*	0.713	0.720	0.723	0.743	0.721	**0.724**
0.3	*0.6*	0.672	0.691	0.703	0.716	0.691	**0.695**
0.6	*0.3*	0.715	0.717	0.700	0.715	0.694	**0.708**
0.6	*0.6*	0.628	0.665	0.666	0.701	0.682	**0.668**

Tab. 6.9. Pedestrian comfort for Different Combination of Parameters.
Simulation with different random seeds and average value.

To identify the best parameter set, single performance indicators are joined together into a single error statistic E_j, which consists of the sum of respective errors [Eq. (6.3)]:

$$E_j = \left| \frac{VD_{sim} - VD_{ref}}{VD_{ref}} \right| + \left| \frac{PC_{sim} - PC_{ref}}{PC_{ref}} \right| \tag{6.3}$$

where the subscript ref is for reference and sim is for simulated. To estimate the optimum solution, a bilinear interpolation within the selected range is used. Contour lines of the error E_j over r_{vp} and r_{pv} are plotted in Fig. 6.8 in which the point r_{vp}= 0.43 / r_{pv}= 0.55) represents the minimum of the function (with E_j=0.03).

Validation of parameters should usually be performed on another data set with different characteristics of traffic (e.g., different flow rates). However, during the 30-min time interval traffic was found to be quite homogeneous. Moreover, dividing the data into two subsets (one for calibration and one for validation) would have weakened the robustness of calibrated data. For this reason, in the current application, the validation simply consists in running the simulation by imposing the estimated values for parameters r_{vp} and r_{pv}. As shown in Tab. 6.10, the average *VD* and *PC* do not differ consistently from the observed ones (error less that 3%).

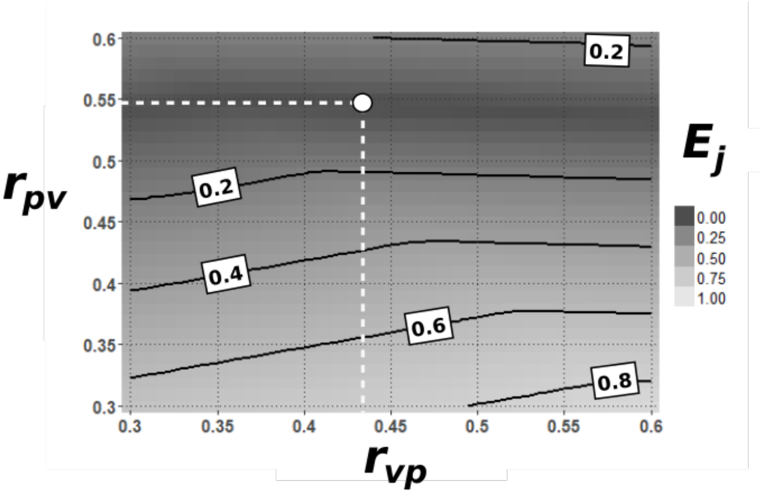


Fig. 6.8. Contour lines for E_j. Minimum point in white color.

Performance Indicator	Value by random seed..					Result	
	1	2	3	4	5	Mean	Error [%]
VD	8.88	14.97	7.95	10.61	10.71	**10.62**	2.5
PC	0.696	0.697	0.713	0.723	0.722	**0.708**	2.7

Tab. 6.10. Mean value and error of the *VD* and *PC* with the estimated values of r_{vp} and r_{pv} .

7 Alternative analysis

This chapter is dedicated to the performance evaluation of alternative scenarios. The microsimulation model developed in Chap. 5 and calibrated in Chap. 6 is used to run the simulations. The output of the simulations is post-processed, and the *MOEs* selected in Chap. 4 are computed and discussed. The analysis of "project alternatives", as referred to by the *FHWA* [25], comprises four different steps, as follows.

1. Definition of baseline and alternative scenarios. To properly evaluate the benefits or drawbacks of alternative scenarios, the baseline must reflect the characteristics of current traffic supply, as road design and regulation. Traffic demand can eventually be adapted to account for future variations. On the contrary, alternative scenarios reflect operational strategies and/or geometric improvements and are based on direction from the decision-makers.

2. Selection of measures of effectiveness (*MOEs*). As discussed in Chap. 4, proper performance measures are needed to evaluate to what extent an alternative fulfills project objectives. The comparison of this measures provides the basis for the evaluation.

3. Model applications (simulation runs). The microsimulation model is employed to compute the *MOEs* for each alternative. The specific manner to run simulations must be properly defined.

4. Post-processing of simulation output and evaluation. While visual output provides a powerful instrument for a qualitative analysis, the output numeric file -containing the position of road users at every time step - is needed to compute the *MOEs*. Here, this operation is called "post-processing". By comparison of these data with those from baseline, the evaluation of alternatives is performed.

While this subdivision generally describes any microsimulation project, in this chapter the specificities of the shared space case are discussed. Sec. 7.1 presents a methodology for alternative analysis, from the definition of scenarios and *MOEs*, to the model applications and analysis of results. Single subsections address the above-mentioned steps. Moreover, an application of the developed methodology to the current case study is provided, both with shared space scenarios (in Sec. 7.2) and conventional ones (in Sec. 7.3). For both, representative alternatives to the baseline were chosen.

7.1 Methodology

The single steps to perform the alternative analysis for shared spaces are discussed in the subsections Sec. 7.1.1 to 7.1.4. In Sec. 7.1.5, the specific choices for the current case study are presented and motivated.

7.1.1 Definition of scenarios

Baseline scenario correspond to the existing road design and regulation. Since shared spaces are usually the result of street redevelopment, the baseline should correspond to the existing conventional design.

Two classes of alternative scenarios can be represented, i.e. not only shared space (single surface) but also conventional ones (with physical segregation). The reason is that the benefits of a shared space must be supported by results and evaluated in comparison with conventional scenarios, which still represent an alternative to consider.

The classes of instruments identified in Sec. 2.2.3 are used to define shared space alternatives, which are itemized in the following:

- **Street design:** Includes the position and extension of the circulation zone (the part of the road section to share), the number of lanes for vehicles (one-way or two-way), and eventually the distance between lanes.

- **Road regulation:** Consists on the variation of speed limits (usually 10, 20, or 30 km/h). Moreover, any road regulation can be potentially simulated, as long as the model realistically reproduces the expected behavior of road users (especially the conflict decision model, which addresses priority mechanisms).

- **Traffic demand:** Refers to the variation of flow rate for each type of road user. In fact, while for conventional streets usually the rush hour is tested (it actually represents the worst case), in shared spaces this issue is more complex. For the traffic performances, the ratio between vehicle and pedestrian flow rate appears, indeed, to be more important than the absolute flow rate itself. This matter has been treated in Sec. 2.2.3 and highlights the necessity to test the influence of varying flow rate in traffic performances.

Conventional scenarios are based on space segregation and specific crossing facilities for pedestrians. Priority-based crossing facilities should be tested, as zebra crossing (pedestrian priority) or refuge island (vehicle priority). Traffic lights are more balanced solutions (priority alternates over time), and green times can be adapted depending on traffic flows.

7.1.2 Selection of MOEs

The question about which *MOEs* to employ for shared space simulation has been widely discussed in Chap. 4. Vehicle delay (*VD*) and pedestrian comfort (*PC*) were selected for traffic quality, while surrogate safety measures (*SSMs*) were chosen for traffic safety. The basic principle is to use the same measures for baseline and all selected alternatives, so that comparison is possible.

Nevertheless, it points out that *PC* was calibrated with shared space data. It follows that, for conventional scenarios, the formulation and the meaning of *PC* need to be reconsidered. The basic formulation of *PC* [see Eq. (4.8)] is conflict-based, while the alternative formulation [see Eq. (4.10)] is conflict-free. The first emphasizes the interaction between pedestrians and motorists; the second emphasizes the directional change. As a consequence, the analyst must properly evaluate which aspect to consider, regardless of traffic conflicts or directional change. When considering scenarios with traffic lights, it must be reminded that traffic conflicts do not occur. Instead, directional change is required to reach the place where crossing facility is located. For this reason, when including traffic lights as scenarios, the alternative formulation can provide more meaningful results: In shared spaces, directional changes occur in every possible way - depending on traffic conflicts, indeed - while by traffic lights they are unavoidable, despite being smooth and at low speeds. If necessary, traffic conflicts could eventually be considered separately in the traffic safety analysis by the computation of *SSMs*.

7.1.3 Simulation runs

As soon as scenarios and *MOEs* have been selected, the analyst can proceed with the simulation run. Three key considerations must be taken in this regard:

- **Simulation time:** Usually simulation covers time intervals of 1 hr, which reflects the rush-hour period. Nevertheless, this value can be reduced depending on project scope and computational constraints.

- **Number of required simulations:** It is necessary to run the model several times with different random number seeds, since no single simulation run can be expected to reflect any specific field condition. The output of single simulation can vary by 25% percent and higher standard deviations may be expected when traffic flow is close to capacity [25]. Mathematical methods can be employed to calculate the required number of simulations for a given scenario, which is strongly affected by the selected simulation time.

- **Post-processing interval:** The initial period of the simulation should be excluded from the computation of results, since standard traffic conditions are not reached yet and road users are being generated.

7.1.4 Results and evaluation

For every simulation run, the *MOEs* are computed for each road user. Successively, two data aggregations are performed: first, among road users, to obtain one value of each *MOE* for each simulation; second, among simulations, to get one value of each *MOE* for each scenario. The aggregation method consists of the simple mean. Successively, the evaluation of scenarios is performed by comparison of aggregated *MOEs*. The selection of the "best" scenario should reflect the project scope.

7.1.5 Specifications for the current case study

In the current application, the existing shared space in Bergedorf, Hamburg, was chosen as baseline scenario. Traffic supply reflects the actual design and regulation, while traffic demand consists of the collected values of flow rate and O/D positions, both for vehicles and pedestrians. Baseline scenarios should correspond to conventional designs; however, the shared space baseline was chosen since it corresponded to the existing case. Opposingly, alternative scenarios are both with shared spaces as with conventional designs.

Among shared space alternatives, a sensitivity analysis of traffic performances is created for the following variables:

- **Flow rates:** Both for vehicles (proportionally for both lanes) and for crossing pedestrians (proportionally for all O/D relationship). The choice to focus on traffic demand was made to better investigate one of the main issues about shared space, i.e., how the number of road users affects traffic performance, as well as the ratio of pedestrians/vehicles.

- **Extension of the shared zone:** Starting from 63 m of the current design, the extension is reduced until 10 m by the condition to preserve the area in front of the station entrance (where the majority of pedestrians cross). In the standard praxis, this fundamental choice is made by analyzing the characteristics of pedestrian traffic demand, e.g., by tracing desire lines [80]. However, it is not clear how the variation of the extension would affect performances. Microsimulation could investigate this matter for this reason, this parameter is chosen and a sensitivity analysis is performed.

Among conventional design alternatives, two pedestrian crossing facilities are simulated:

- **Zebra crossing:** This facility assigns priority to crossing pedestrians, while drivers must yield.
- **Refuge island:** This facility assigns priority to driving vehicles, while pedestrians must wait for sufficient temporal gaps to cross the street.

The alternative formulation of pedestrian comfort (*PC*) is chosen as *MOE* for pedestrians. There are three main reasons. First, traffic light scenarios are included in the simulation, and the aspect of directional change was assumed to be more relevant than conflict themselves. Second, conflicts are investigated apart by *SSMs* within traffic safety performance evaluation. Third, due to high flow rates, there are concerns that the developed model does not realistically represent traffic conflicts. The last point is discussed more clearly in the next paragraph.

As flow rates increase, the probability of multiple conflict situations arises. For this task, the model developed in Sec. 5.5.4 comes into play. For the same type of *CUs*, a modeling approach was proposed, but no calibration was carried out (contrarily, the choice model for single conflicts was calibrated). Moreover, for different types of *CUs*, a strong approximation was taken (i.e., only the conflict closer in time is evaluated by the *EU*). In this sense, the model has not been not sufficiently developed and tested to guarantee realistic performance. This was visible in the animation output, in which pedestrians and vehicles overlapped each other, on occasion. Given that the first *PC* formulation considers the worst conflict of the road user's travel, this fact would have led to unrealistic results, making *PC* critically sink to the minimum. By considering the alternative formulation, this problem would still persist; nevertheless, the effect on performances would be less acute. This is also the reason why *SSMs* were not computed for shared spaces. In future research, with more realistic models for multiple conflicts, this problem can be overcome.

Shared space simulation was repeated for each scenario for a period of 2 min. Given the high computational effort - especially by high flow rates - it was not possible to simulate longer intervals. In fact, substantial slowdowns of simulation occurred as the number of road users increased, making the software investigate and solve high amounts of conflicts. For conventional scenarios, which were simulated with the software PTV VISSIM, this problem did not occur, and the simulation of 1 hr intervals was carried out.

Given the temporal limitation of shared space simulations, an investigation of the necessary number of simulations with different random seeds was performed. For conventional scenarios, this step was not necessary - since simulation times were much longer - and a standard number of five repetitions was assumed as sufficient.

By post-processing simulation data, the first 20 s of shared space simulation were excluded. For conventional ones, the first 2 min were discarded.

7.2 Application: Shared space scenarios

To introduce stochasticity in shared space simulation, some attributes defined in the *.xml* input files, which describes traffic demand, were randomized in the following way:

- The desired speed of road users was randomly chosen within a normal distribution, with mean as the calculated desired speed (see Sec. 3.4 and standard deviation equal to 0.2.
- The initial position (origin) of pedestrians was randomize around the given centroid within a radius of 4 m.
- The time of appearance of road users in the simulation was randomly selected within the available simulation time of 120 s. For vehicles driving in the same lane, 2 s were imposed as minimum time headway to avoid overlapping

The randomization was initialized by defining a random seed, which uniquely defines an *.xml* input file belonging to the same scenario.

As mentioned above, the necessary number of simulations to obtain stable results was determined. The baseline scenario was simulated 10 times by different random seeds, and the performance indicators were computed. The results are shown in Fig. 7.1, where the black solid line represents the mean value and the gray dotted ones the 0.15 and 0.85 quantile. The mean value was assumed to correspond to the “real” output of the simulation. It noted how the value of *PC* is more stable than *VD*, whose high variance is a consequence of the short simulation times. This suggests that the number of required simulations will be essentially a matter of *VD*.

The question is, then, how many simulations are needed to obtain the mean values (assumed as reference) with a certain approximation. To discover this, a statistical method was employed to infer the necessary number of runs n to reach the reference values with 5% of error at most. For every $i = 1..n$, all possible combinations k of the i elements were

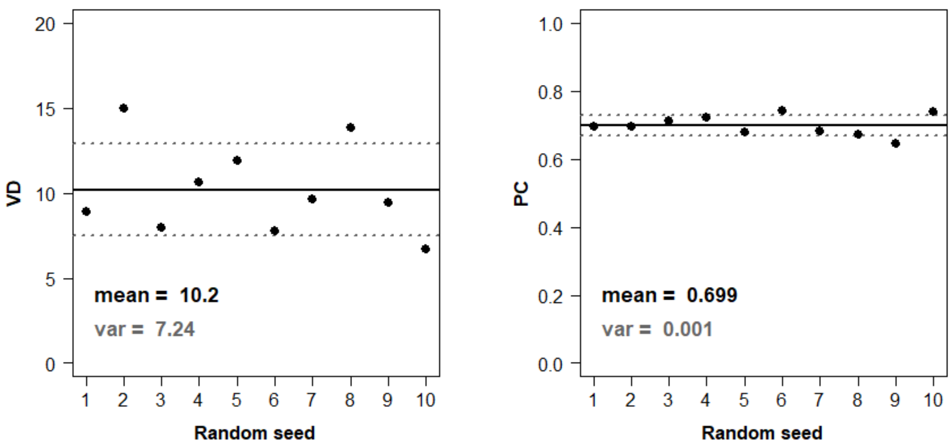


Fig. 7.1. Results of 10 simulation runs for the baseline scenario: values of VD (left), PC (right)

computed, and the mean performance value was calculated. Successively, the error to reference values was averaged among all combinations. This consists of the mean error that is committed by randomly choosing only i elements from the sample. The results are shown in Fig. 7.2, in which the mean error is plotted over the number of elements i. The 5% error is depicted by a red dashed line. The results show that, despite *PC* being quite stable and the error small, for *VD* the threshold if 5% is reached by at least seven simulations.

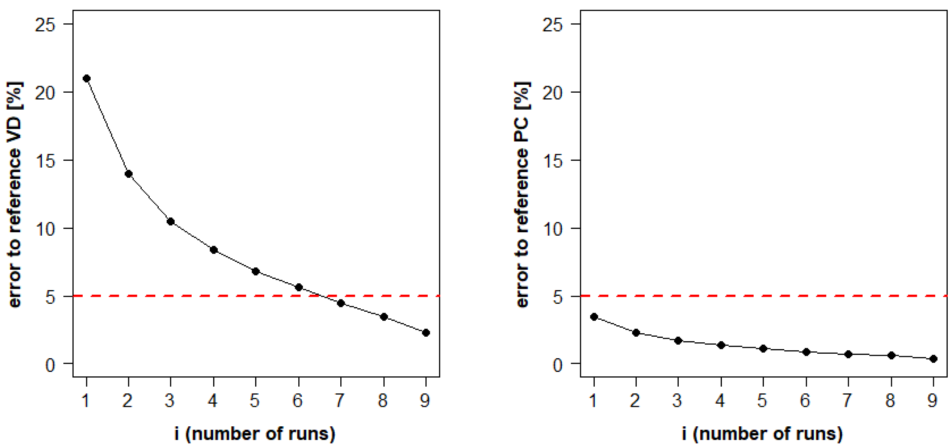


Fig. 7.2. Error to reference performance values for i simulation runs: VD (left), PC (right)

For this reason, for every scenario seven simulation runs are performed, with corresponding random seeds and *.xml* input files. Therefore, the final values of *PC* and *VD* are computed as the average of seven simulation runs.

7.2.1 Traffic quality

The computation of shared space performances is carried out by investigating the effect of single factors one at a time. While the choice of specific factors is presented in Sec. 7.1.5, a summary of the range investigated in the sensitivity analysis is provided in Tab. 7.1 (reference values reflect the data survey).

Factor	unit	Reference value	Tested values
Vehicle flow rate	[veh/h]	600	100, 200, 400, 800, 1000
Pedestrian flow rate	[ped/h]	2100	700, 1400, 2800
Shared zone extension	[m]	63	20, 30, 40, 50

Tab. 7.1. List of factors tested in the sensitivity analysis: Reference and tested values

The effect of vehicle flow rate on traffic quality is investigated at first. Logically it can be expected that higher traffic volumes negatively affect traffic quality. This expectation is confirmed in Fig. 7.3, in which the *VD* (left) and *PC* (right) are plotted for the increasing value of vehicle flow rate. In order to investigate the significance of the relationship between dependent and independent variables, a regression analysis is performed. The *p*-value is calculated under the null hypothesis that the regression coefficient is equal to zero (no effect). When the *p*-value is lower than 0.05, the null hypothesis is rejected and the relationship is assumed to be significant. In this case, the *R-squared* is displayed and the slope of the regression line is represented.

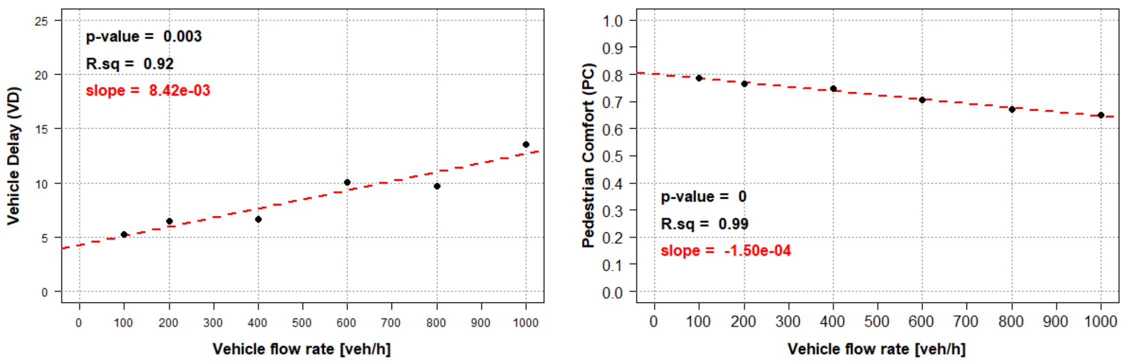


Fig. 7.3. Influence of vehicle flow rate on Vehicle Delay (left), Pedestrian Comfort (right)

As the *p*-value indicates, the flow rate of vehicles affects vehicle delay. This can be reasonably explained by the intensification of queuing. The relationship between pedestrian comfort and vehicle flow rate is also significant. Furthermore, points appear to be quite aligned (*R-squared* = 0.99). While on a general level this result is reasonable, it is still interesting to investigate which specific aspects make *PC* decrease. With this purpose, the effect of single terms in Eq.(4.10) - *D* (delay), *TE1* (vehicle presence) and *PM1* (amount of deviations) - is investigated. For this purpose, an ideal crossing with no delay (D=0), no vehicles around ($TE1$=0), and no deviations ($PM1$=0) is taken. In this case, *PC* is approximately 0.85. When the value of single factors differs to 0, *PC* decreases. In order to investigate how single factors negatively affect the overall traffic quality for pedestrians, the relative decrease of

PC Δ_k - with reference to the ideal crossing - due to the factor k among all factors $i = 1..n$ is computed as in Eq.(7.1).

$$\Delta_k = PC(x_i = 0 \mid \forall i) - PC(x_i \neq 0 \mid i = k, x_i = 0 \mid i \neq k) \tag{7.1}$$

The value of Δ_k is plotted in Fig. 7.4 for different vehicle flow rates.

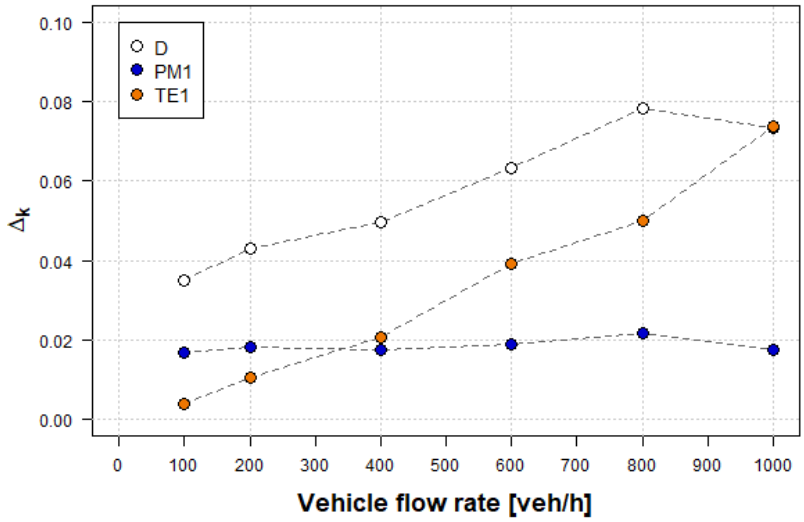


Fig. 7.4. Negative contribution of terms on pedestrian comfort

As flow rate increases, the value of *TE1* increases accordingly. This is quite predictable, since the more vehicles are introduced in the road section, the more vehicles would flow around pedestrians in average. Starting from Δ_{TE1} close to zero for low flow rates, this negative contribution reaches the value of 0.8 for 1000 vehicles per hr. The contributions of path deviations (Δ_{PM1}) is approximately stable and is not affected by the flow rate. On the contrary, delay D plays a major role in determining comfort. Even for low flow rates, the contribution of delay time is not negligible. This is explainable by the fact that, when flow rate is low, vehicles drive at higher speed, which discourages pedestrians from crossing the road and causing delays. As flow rate increases, delay certainly arises, but this factor is softened by lower mean driving speed, which encourages pedestrians to take priority. Moreover, from 800 veh/h D is stable, which can be explained by the presence of strong congestion - vehicles stay in queue and do not additionally hinder pedestrians while crossing.

The effect of flow rate of crossing pedestrians on traffic quality is depicted in Fig. 7.5. For *VD* and *PC*, the test for statistical significance shows that a relation between dependent and independent variable exists (*P*-value < 0.05). Moreover, the linear model explains the model very well (R-squared > 0.98). Therefore, it can be stated that higher volumes of crossing pedestrians have negative impacts on traffic quality, both for vehicles and the same pedestrians.

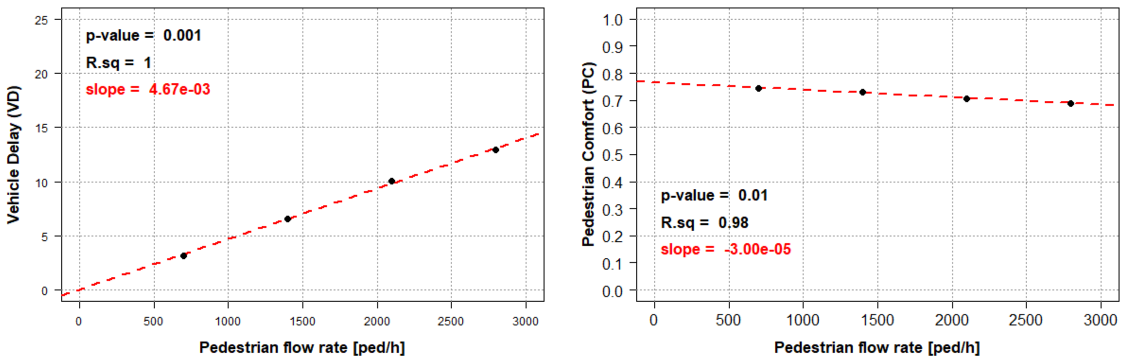


Fig. 7.5. Influence of Crossing rate on Vehicle Delay (left), Pedestrian Comfort (right)

As pedestrian flow rate increases, drivers tend to slow down more often to allow pedestrians to cross. The regression line represents this effect quite well, returning no delay (close to 0) when no pedestrian is crossing, while a 15 s delay is returned for 3000 ped/h. With respect to pedestrian traffic quality, higher flow rates cause two major effects. On the one hand, they increase pedestrian "strength" over vehicles, therefore forcing drivers to yield. This aspect would decrease crossing time. However, higher pedestrian flow rates also increase density, which results in lower degrees of freedom and, more general, a more hindered motion. For this reason, the value of Δ_D in Fig. 7.6 is increasing. Moreover, Δ_{TE1} increases since motorists tend to yield more often when the number of pedestrians increases. The contribution of directional changes (Δ_{PM1}) is negligible again. It can be concluded that higher pedestrians flows negatively affect the traffic quality of pedestrians, despite being slight, i.e., the slope is around e-05.

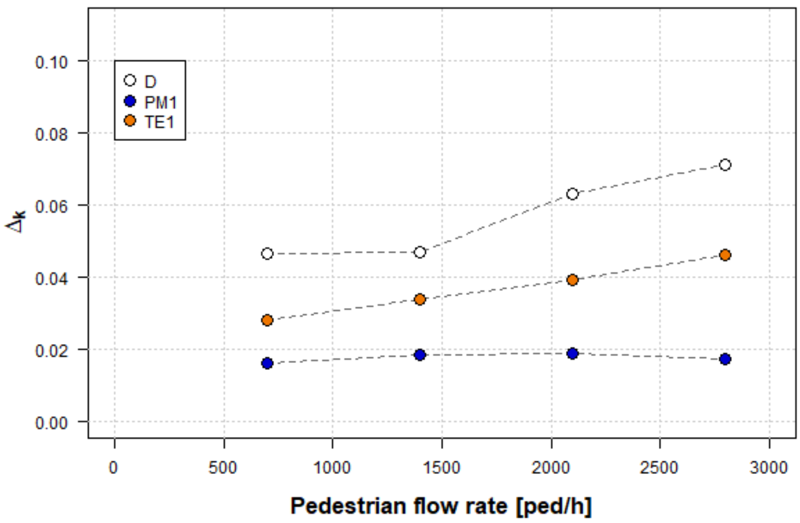


Fig. 7.6. Negative contribution of single variables on Pedestrian Comfort

Finally, the extension of the shared zone is investigated. As shown in Fig. 7.7, this factor influences *PC* but not *VD*. In the latter case, the *p*-value is definitively over the threshold value of 0.05 and the null hypothesis cannot be rejected.

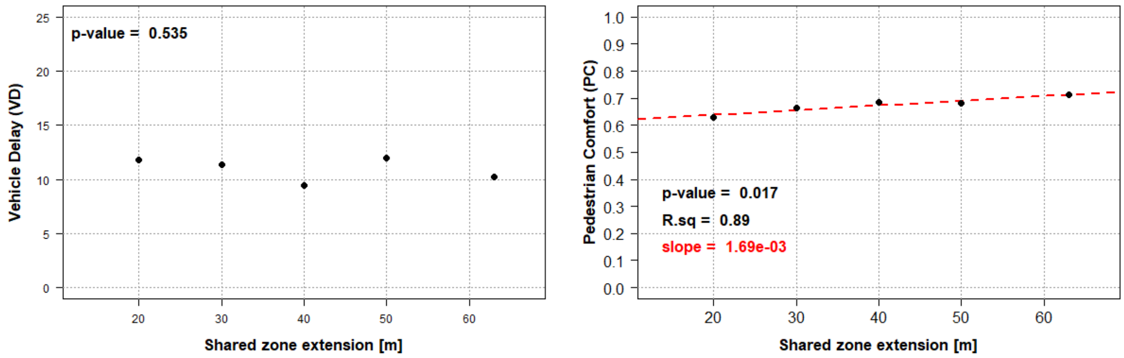


Fig. 7.7. Influence of the length of shared zone on Vehicle Delay (left), Pedestrian Comfort (right)

As the extension of the shared zone decreases, pedestrians must consequently adjust their path increasingly to cross where it is allowed. This increases the delay D, i.e., more time to reach the destination, but also the deviation rate (see Fig. 7.8). Moreover, if the shared zone is limited, by the same value of vehicle flow rate more queuing is expected. This also makes the factor (Δ_{TE1}) slightly increase. It can be concluded that, for the reference flow rates of vehicles and pedestrians, the more the shared zone is restricted, the lower Pedestrian Comfort is, while Vehicle Delay generally remains constant.

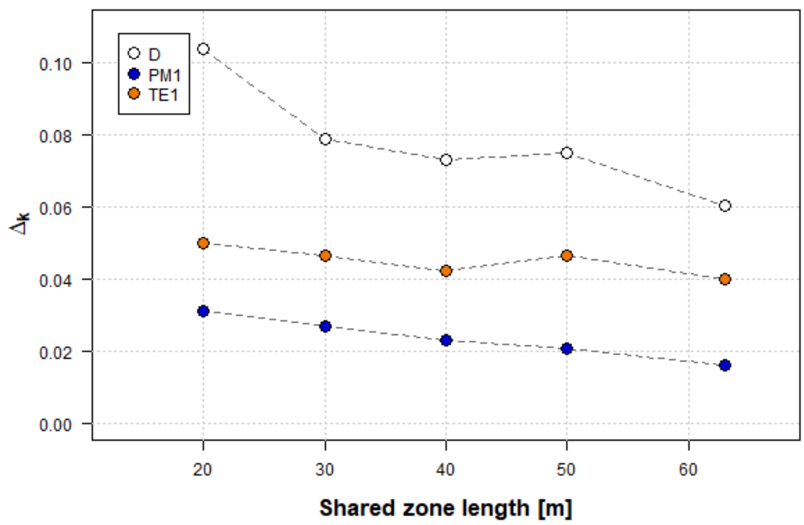


Fig. 7.8. Negative contribution of single variables on Pedestrian Comfort

Conclusion

Single sensitivity analysis has shown that, with the current reference values, pedestrian comfort is expected to decrease when traffic volumes increase - for vehicles and for pedestrians - as well as when the extension of the shared zone is reduced. Moreover, the delay of vehicles arises as traffic volumes increase. Instead, the length of the shared zone does not affect vehicle delay.

It must be reminded that the presented results have involved one factor at a time, while keeping the other factors fixed with the reference value. For this reason, results may differ for different combinations of factors; further, the presented conclusions cannot be generalized to all situations.

7.3 Application: Conventional scenarios

An alternative to the type of shared space addressed in this thesis, “conventional” crossing facilities can be provided to let pedestrians move from one side to the other of the roadway. The main difference is represented by the position where the crossing takes place, which is predefined and imposed - at a given location along the road section - instead of being set free. Interaction rules also change: While shared spaces are aimed at promoting the logic of space negotiation, with crossing facilities, specific priority rules are set to regulate interaction.

Refuge islands or curb extensions force pedestrians to wait until an acceptable time gap between vehicles is found, i.e., motorists have priority. Via zebra crossing, instead, motorists are forced to yield when a pedestrian is on the road side, i.e., pedestrians have priority. These types of crossing facilities, which assign priority either to the longitudinal flow or to the crossing one, are generally suitable when operating speed as well as traffic demand is low. As a reference, the Richtlinien für die Anlage von Stadtstraßen [77] recommends specific conditions for their applicability, which can be determined by combining the operating speed with the pedestrian flow rate as well as that of motorists. The calculation can be performed via Tab. 77 of the guidelines and is helpful to identify ranges of suitability. According to this method, courtesy crossings require generally stricter conditions of driving speed and traffic flows, while refuge islands are slighter less restrictive. When driving speed and (-or) traffic flows increase, refuge islands are more suitable, because they allow one to split the crossing movement in two phases. In this case, the method is run again to determine if a zebra crossing has to be provided as well. Further, when these ranges are exceeded, it is recommended to assign priority to flows in separated temporal intervals through traffic lights.

The focus of this section is to simulate and evaluate "conventional" crossing facilities, which can implemented in place of shared spaces. In this regard, the aim is to provide a method to compute the *MOEs* - in the field of traffic quality and safety - as developed in Chap-. 4. In this way, the evaluation and comparison between shared spaces and "conventional" crossings can be accomplished through indicators of the same type (i.e., which catch the same aspects).

In line with this thinking, a traffic light can be excluded from the analysis. The reason is that boundary conditions as well as purposes to implement shared spaces differ significantly from those of traffic lights. From the perspective of traffic demand, traffic lights are set when the flow rate of vehicles is high, while shared spaces presuppose limited ones. Moreover, traffic lights are set to provide a possibility to cross when vehicular traffic is not "calmed", namely, when posted speed is higher that 30 km/h. Instead, shared spaces are measures of traffic calming and presuppose low driving speeds. Given that the context is quite different, the question of implementing shared spaces or traffic lights usually do not occur.

When vehicular traffic is restrained and traffic calming is an objective of street redevelopment, unsignalized crossing come into question. For this reason, these types of crossing facilities are investigated here, with a focus on two of them, which are assumed to be representative. On the one hand, zebra crossings were considered because of their characteristics to favor the movement of pedestrians at the expense of drivers, who are forced to yield. On the other hand, refuge islands without additional measures are tested for the following reasons: first, contrarily to pedestrian crossings, they assign priority to vehicular traffic; second, they offer pedestrians the benefit to split the movement into two phases, meaning that pedestrians are not excessively penalized.

Bergedorf's actual design scheme was modified by superimposing the specific crossing facilities. The position of the crossing facility was chosen with the aim to minimize detours for pedestrians: This was carried out by intersecting the roadway's midline with the computed desire lines and by calculating the centroid among those points. Given the purpose to shorten pedestrian routes as much as possible, the width of the crosswalk was set to 10 m for all cases, which correspond to the maximum allowed by law in Germany. The refuge island was set with 2 meters width, so that pedestrians would have enough time to evaluate temporal gaps in the second lane. Consequently, vehicle lanes were deviated smoothly before and after the crossing position.

The conventional alternatives were simulated with the software PTV VISSIM. For the computation of performance indicators, both for traffic quality and safety, the simulation was reproduced five times with different random seeds, and the output was averaged. The results of conventional scenarios are described in Sec. 7.3.1 for traffic quality and Sec. 7.3.2 for traffic safety.

7.3.1 Traffic quality

In order to show an exemplary application of the method, conventional scenarios were simulated with the same traffic demand of the baseline. The computation of pedestrian comfort (*PC*) follows the approach of the standard formulation [Eq. (4.8)], which considers traffic conflicts. In fact, despite other dynamics as in shared spaces, traffic conflicts also occur by crossing facilities, i.e., the road user without priority has to yield by performing an evasive action. This conflict, as well as the reaction, is more or less severe depending on a number of factors, which could be road user specific (e.g., the attitude to risk) but also context specific (e.g., operating speed and flow rate). For this reason, it makes sense to imply conflict-related parameters (*IV2* and *IV3*) in the computation of pedestrian traffic quality.

The results are shown in Tab. 7.2 with the corresponding Level Of Service. Moreover, the values of single factors implied in the computation of *PC* are shown in the columns *D*, *TE1*, *IV2*, and *IV3*.

	Vehicles		Pedestrians					
	VD	LOS	D	TE1	IV2	IV3	PC	LOS
Zebra crossing	**>45**	**E**	3.18	6.76	3.42	5.9	**0.58**	**C**
Refuge island	**6.74**	**A**	9.32	1.47	2.34	4.69	**0.54**	**D**

Tab. 7.2. Traffic quality for “conventional” crossing facilities with the traffic volumes as in the baseline scenario

	D	TE1	IA2	IA3
Zebra crossing	0.62 (-12%)	0.47 (**-34%**)	0.78 (+10%)	0.78 (+10%)
Refuge island	0.46 (-35%)	0.66 (-7%)	0.76 (+7%)	0.77 (+9%)

Tab. 7.3. Effect of single variables on PC (baseline=0.71)

As expected, zebra crossings appear to be inconvenient for motorists (*LOS* = E). The number of crossing pedestrians, which exceeded 2000 ped/h, is too high to preserve the flow of vehicles. In the simulation, queues are forming close to the crossing facilities, causing extreme high delays. Moreover, traffic quality for pedestrians is not as high as one would expect (*LOS* = C). This can be better inspected in Tab. 7.3, in which the contribution of single factors on the value of *PC* is shown. For both crossing facilities, the number in the first line shows the potential value of *PC* when only the factor at the top of the column is considered. Moreover, the percentage in parenthesis shows the relative increase (or decrease) in comparison with the baseline value of 0.71. Despite pedestrians having priority, delay makes the indicator decrease by 12%, which is due to the necessity to move to the crossing location instead of crossing at the desired point. This increases the length of the path and, consequently, delays. Moreover, the negative contribution of factor *TE1* is remarkable (-34%): long queues give the perception of a congested environment, which increases discomfort. These effects are softened by the lack of apprehensive conflict situations (*IV2* and *IV3* both contribute with +10%).

On the other hand, a refuge island provides high traffic quality for motorists (*LOS* = A) and also sufficient traffic quality for pedestrians (*LOS* = D). The flow of vehicles is almost uninterrupted. A delay of around 7 s is caused by decelerations to yield to pedestrians who already left the roadside. Delay of pedestrians is the highest contribution that affects *PC* (-35%), which is caused by long paths (as by zebra crossing) and, additionally, by the time needed to wait for acceptable time gaps. In comparison with zebra crossing, conflicts with vehicles are more severe (see the value of *IV2* and *IV3*), which results in a slightly lower positive contribution to *PC* (respectively, +7% and +9%).

With respect to the focus of this dissertation, it must be remarked that traffic quality would differ if only delay time were considered. In this case, almost 10 s of delay were required on average for a pedestrian to cross the road, instead of 3 s by a refuge island. By employing the new developed *MOE*, traffic quality by zebra crossing decreases because of the presence of vehicles, thus softening the difference in performances with the refuge island.

7.3.2 Traffic safety

This subsection focuses on the evaluation of traffic safety through surrogate safety measures (*SSMs*). The purpose is to provide an application of the theory and principles developed in Sec. 4.2 as well as to show the straightforwardness of this method. To avoid queuing situations, and therefore to obtain clear yielding behavior, the traffic volumes were imposed as 50% of the baseline scenario. To reduce computing times - the analysis of conflicts is time consuming - only one 30 min simulation pro scenario was performed - i.e., one random seed. After the simulation, conflict situations are detected, and *SSMs* are computed for each conflict. According to the definition provided in Chap. 4, a conflict is defined as an interaction in which two users would collide ($d_c^* < 2$ m), and Time To Collision is lower than 5 s.

The first result to inspect for safety analysis consists of the absolute number of conflicts within the simulation time. Via zebra crossing, this number is higher with respect to refuge island (649 vs. 469). However, this information is meaningless if the severity of the conflict is not inspected.

Time To Collision is plotted in Fig. 7.9 for zebra crossing (left) and refuge island (right). For both, the majority of conflict situations happens by *TTC* between 1 and 3 s. Moreover, it can be noted that, in a refuge island, more high-severity conflicts ($TTC < 1$s) occurred with respect to the zebra crossing. Results are also provided in Tab. 7.4 with the percentage among total conflicts. The mode is indicated in bold.

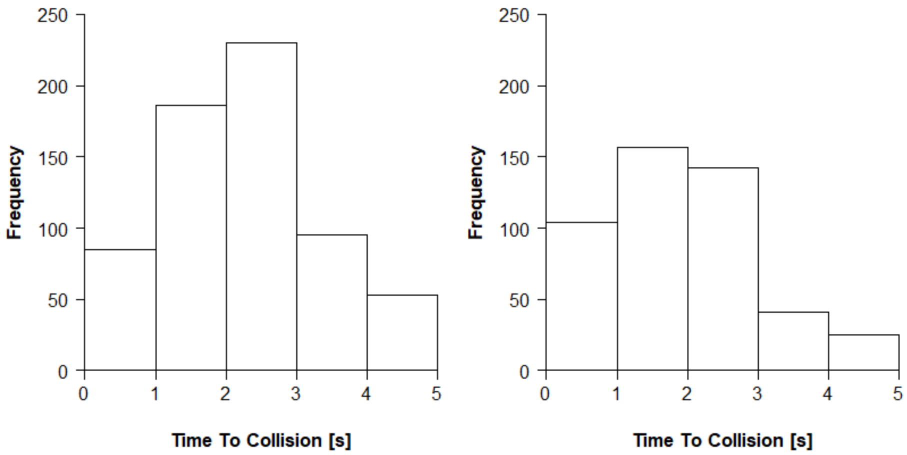


Fig. 7.9. Distribution of Time To collision: zebra crossing (left), refuge island, right

Type	Total	[0;1[	[1;2[	[2;3[	[3;4[	[4;5]
Zebra crossing	649	0.13	0.29	**0.35**	0.15	0.08
Refuge island	469	0.22	**0.33**	0.3	0.08	0.06

Tab. 7.4. Distribution of Time To Collision, percentage among all conflicts

For the analysis of post-encroachment time (*PET*) and vehicle speed (*VS*) the analyst should focus only on the most severe conflicts ($TTC < 2$). In fact, in these circumstances, collision is more likely to happen: It is therefore more meaningful to evaluate how close road users were about to collide (through *PET*) and how intense the consequences would have been in the case of collision (through *VS*).

First, the number of most severe conflicts is determined. This amounted to 252 for a zebra crossing (39% of total conflicts) and 239 for a refuge island (51% of the total). That means, more conflicts occur in a zebra crossing, but they are generally less severe.

The distribution of PET is shown in Tab. 7.5 by ranges of 2 s.

Type	Total	[0;2[	[2;4[	[4;6[	>=6
Zebra crossing	252	0.09	0.19	0.07	**0.65**
Refuge island	239	0.02	**0.69**	0.17	0.12

Tab. 7.5. Distribution of Post Encroachment Time, percentage among severe conflicts

Conflicts in refuge islands are generally more severe than in zebra crossings (71% of *PET* is lower than 4 s in comparison with 28%). The reason is that, via zebra crossing, vehicles are forced to give way; therefore, they need to reduce the speed - even up to a stop. This is also visible in the distribution of vehicle speed (*VS*) in Tab. 7.6, where the 84% of them is lower than 20 km/h (in comparison with the 14% by refuge island).

Type	Total	[0;10[	[10;20[	[20;30[	>=30
Zebra crossing	252	0.36	**0.48**	0.14	0.01
Refuge island	239	0.01	0.13	**0.82**	0.03

Tab. 7.6. Distribution of vehicle speed, percentage among severe conflicts

Generally, when vehicle speed is lower and vehicles have to decelerate - or even to stop - to yield to pedestrians, conflicts are, consequently, less severe. This is also reflected by the distribution of *TTC* and *PET*, which indicates that, by this level of traffic demand, the zebra crossing is relatively "safer" than a refuge island.

Conclusions

8

8.1 Summary

In this dissertation, a method to evaluate the performances of shared spaces through traffic microsimulation was proposed. Among the high variety of configurations of shared space, we chose to focus on the longitudinal, namely, road sections without curbstones and bidirectional traffic. The motivation behind this work is that traffic engineers need precise results to evaluate shared spaces and to assess their suitability in comparison with "conventional-designed" streets. The problem is that shared spaces not only have the features of classical road environments (i.e., with movement function), but they are also public spaces in which perception and comfort of pedestrians is fundamental for the success of these areas. Therefore, employing efficiency-based performance measures, e.g., delay time, would catch the objective of this street design only marginally. The challenge was, consequently, to integrate efficiency-based indicators with aspects of pedestrian comfort. Moreover, to demonstrate the effectiveness of the developed measures, it was aimed to apply the developed indicator on the result of traffic microsimulation on a real-world case study.

This thesis started with a detailed review of shared space design and aims, which was carried out via national guidelines and scientific literature. It emerged that goals of shared space design are the improvement of pedestrian condition - in particular, movement and comfort - and traffic safety. The objectives, namely, strategies to achieve goals, are the reduction of vehicle dominance and the increase of space sharing. The instruments, namely concrete measures to achieve objectives, are to operate on street design, road regulations, and traffic demand.

The classification in goals, objectives and instruments as well as in the interconnections among classes was formulated for two main reasons: First, to develop a measure of effectiveness (*MOEs*) which reflects the goals; second, to identify reasonable "alternative" shared space scenariosm which reflect the instruments available for traffic engineers. Moreover, a literature review of performance evaluation methods and shared space microsimulation was provided.

A street designed as shared space in the district of Bergedorf, in Hamburg (D), was chosen as the reference case study. The selection of the site was due to defined criteria as the intensity of traffic volumes, the configuration as road section, the almost complete absence of cyclists, the de-cluttered features, and the German context. Moreover, despite road regulations (vehicle priority with 20 km/h speed limit), space negotiation with pedestrians effectively occurred. The area was filmed for a period of approximately 3 hr. Successively, all trajectories of pedestrians and vehicles were tracked for a time interval of 30 min, in which the highest traffic demand was observed.

To evaluate traffic quality and safety through microsimulation, proper *MOEs*, which reflect the aim of the study, are required. In light of this, a new *MOE* for pedestrians in shared spaces based on comfort was developed. Three classes of factors are assumed to affect comfort when a pedestrian crosses the circulation zone: first, the presence of other types of road users in the proximity, e.g., vehicles or other pedestrians; second, the presence of conflicts with vehicles during the crossing; third, the necessity to solve conflicts by performing evasive actions. The indicator was calibrated on the basis of the opinion of a group of respondents and by performing a multilinear regression model. It emerged that, when comfort-related aspects are considered, the part of the response explained by the model increases almost 50% in comparison with the model with only time delay as a predictor. Successively, delay time was considered as an adequate measure of traffic quality for vehicles. Finally, a conversion in terms of Level Of Service (*LOS*) was provided.

To simulate shared spaces, a modeling approach based on the social force model (*SFM*) was developed. The lack of classical *SFM* in reproducing the mechanism of space negotiations in shared spaces was identified and shown with real examples. In light of them, a four-layer model was developed with the following layers: free-flow, conflict detection, conflict decision and conflict reaction. The model has been successively implemented as part of the simulation software *MODIS*, which is written in Java.

Two calibration approaches for the developed model were proposed. The first one is the "microcalibration", which provides precise estimations for every parameter but requires a high amount of data. By this method, the parameter S_{vp}, which regulates the braking behavior of vehicles in conflict with pedestrians, was calibrated. The second one is the "macrocalibration", which consist of an adjustment of a restricted number of parameters to fit the simulation results in terms of *MOEs*. By this method, the parameters r_{pc} and r_{pc}, which describe the extension of the short-range interaction in mutual pedestrian-vehicles conflicts, were estimated.

With the developed *MOEs* and the calibrated microsimulation model, alternative scenarios were simulated and performances were estimated. Given the focus of this work on shared road sections, reasonable alternative scenarios were found and motivated. Alternative shared space designs can be constructed by varying space schemes, posted speed limits and intensity of traffic demands. Alternative conventional designs are made by replacing the shared zone with unsignalized crossing facilities for pedestrians, e.g., zebra crossings and refuge islands.

Successively, an application with selected scenarios was provided. Considering the reference scenario of Bergedorf as in the data collection, alternative scenarios were set by varying the intensity of traffic demand and the extension of the shared zone. It emerged that pedestrian comfort (*PC*) is expected to decrease when traffic volumes increase - both that of vehicles and pedestrians - as well as when the extension of the shared zone is reduced. Moreover, the delay of vehicles arises as traffic volumes increase. Instead, the length of the shared zone does not affect vehicle delay.

8.2 Contribution to knowledge and future research

This thesis contributes to the current state of knowledge on shared spaces in three issues, which are discussed below.

1. Pedestrian MOE: comfort vs. time delay

- In Chap. 2, the objectives of shared space design were discussed in light of existing literature and guidelines. Besides the improvement of traffic safety, shared spaces are aimed at increasing pedestrian comfort. With regard to the movement function of streets - on which MOEs are focused - this highlights many other aspects of pedestrian motion which are not purely focused on the "efficiency" of the trip. In other words, walking must be comfortable and pleasant as well as provide safe and quick arrival at a destination. For this reason, it was assumed that pedestrian MOE for traffic quality must also include this aspect. Consequently, in Chap. 4, aspects of walking comfort were postulated, and a mathematical formulation was provided for each one. The regression analysis has confirmed the idea that time delay cannot provide a full picture of traffic quality for pedestrians ($R^2 = 0.45$). By integrating aspects of comfort, the model improves to $R^2 = 0.68$. That means, the inclusion of comfort aspects in the formulation of traffic quality makes the MOE more exhaustive and comprehensive. Therefore, an achievement of this work is the formulation of a new MOE for pedestrian traffic quality, which better fits the aim of shared space design.

- The regression analysis highlighted aspects that influence pedestrian traffic quality in shared spaces. With regard to the presence of other road users, it was found that, as the number of vehicles increases, traffic quality decreases. With regard to traffic conflicts, as the time spent in a conflict situation and the severity of the worst conflict increases, traffic quality decreases. Finally, the reaction to conflict situations is determinant: as the intensity of deviations and deceleration increases, traffic quality decreases. Despite these conclusions being logically predictable, in this work their influence in walking comfort was statistically proved and their extent was calculated.

- The formulation of factors that influence comfort as well as the results of the multi-linear regression were made within the context of shared streets. That means, road sections with a shared space design, in which pedestrians cross from one side of the other the circulation zone, were considered. Instead, when considering shared intersections, the formulation of factors shall be reviewed. In fact, the configuration of the shared zone - a square instead of a stripe - changes the interaction dynamic significantly. Consequently, conflicts and resulting evasive actions occur differently. In light of this, comfort factors require modifications and integrations. Further, the subdivision of factors in three classes according to the key presence-conflict-reaction (i.e., *TE-IV-PM*) remains valid and the developed method to formulate a new MOE can be still used. Finally, with the aim to evaluate every type of shared space, future research should focus on the development of an indicator of pedestrian traffic quality, which is independent from the scheme and which might be a street or intersection.

2. Shared space microsimulation

- The microsimulation approach developed in this thesis is suitable for every shared space configuration. However, specific modeling choices were done to better cover the case of shared streets, which is the focus of this thesis. Examples of these choices are given. First, free-flow trajectories were applied to a path correction, which makes them more perpendicular to the street axis within the circulation zone. Second, no steering model was developed for vehicles, because lane-based behavior was assumed, and the reaction was modeled only by modifications of current driving speed, without deviations. Third, pedestrian evasive actions consider monodirectional traffic, i.e., aggressive and prudent behavior implies the directional change with respect to the street axis, respectively, perpendicular or parallel. To employ the developed model to shared intersections, integrations are necessary. This should consider the different space configuration, the driving direction, the more complex conflict dynamics, and the several possibilities, to perform evasive actions. Nevertheless, the current modeling approach is still valid and can accommodate for these integrations. That means, new conflict-solving strategies and forces can be implemented to the model, but the mechanism for path generation and conflict detection is comprehensive and still exhaustive.

- A decisional model was developed to reproduce the choice of behavioral strategies in pedestrian-vehicle conflicts. The model was calibrated and validated for crossing of the circulation zone in shared spaces. Despite that, the developed approach is also suitable for other types of pedestrian crossings, in which road users are asked to decide whether to cross - or to yield - to the other traffic flow. This type of dynamic occurs, for example, in courtesy crossing, where pedestrians are encouraged to cross despite priority being assigned to vehicles. Moreover, this still happens in zebra crossings. In fact, when the approaching vehicle is too close, the pedestrian may judge the crossing too risky and postpone it. That means, priority rules are clearly defined, but space negotiation still occurs in some circumstances. Therefore, the developed approach can also be employed for conventional crossing facilities and by employing the same predictors identified in this work.

- A modeling approach to reproduce situations where more than two road users interact with each other was also developed. For conflicting users of the same type, the choice of the evasive strategy is determined by aggregating probabilities of single conflicts (i.e., conflicts taken singularly) and comparing the result with threshold values. However, these thresholds were not calibrated and were determined by a mathematical function, which depends on the number of simultaneous conflicts. Instead, for conflicting users of different types, it was assumed that only the conflict closest in time had to be considered, which represents a strong approximation. In light of this, we can state that the issue of modeling multiple conflicts requires further investigation. Future research should focus, first, on analyzing systematically the dynamic of multiple conflicts in various configurations (number and type of road users, relative position) and then on detecting behavioral tendencies. Thereafter, when trajectory data are available, the developed approach can be calibrated and eventually extended.

- Two calibration approaches were proposed for the developed model. The "microcalibration", which is extremely accurate, was applied only to one parameter due to the lack of available empirical data. However, to obtain a microsimulation model which could at least reproduce the same results (i.e., the *MOEs*) of the reality, a "macrocalibration" was proposed, which is more straightforward and less resource and time-consuming. Moreover, the model was not validated. That means, for variation in traffic demand with respect to the reference scenario, model performances are not ensured and can diverge from reality. Validation was not carried out in this work because available data covered only a one-time interval, which was used for calibration. With higher amounts of trajectory data at our disposal, microcalibration could be performed for many other model parameters. Moreover, a method to validate the model can be developed, so that more realistic results can be also obtained in other traffic conditions.

- A lack of the developed shared space model is the exclusion of cyclists as road users. The reason is that this work wanted primarily to focus on pedestrians and vehicles. In fact, in the definition of the aim of shared space design in guidelines, these two categories play a principal role: pedestrian movement and comfort must be promoted, while vehicle dominance must be reduced. Moreover, the success of a shared space is mostly about the fine balance between them. Cyclists certainly contribute to increase the sense of sharing, but the main part is played by the pedestrian-vehicle conflict. According to this, the case study was chosen with few cyclists. Moreover, in the developed modeling approach, cyclists were not considered. Nevertheless, cyclists can be integrated into the model following the structure of the developed framework. In this regard, a modeling approach for cyclists was proposed in the research project MODIS [67]. This included mechanisms of conflict avoidance based on the modification of trajectory and speed, which considers the required curvature for steering. Moreover, other approaches in the literature can be integrated into the developed framework. A summary of researches in this field, i.e., Social Force Model for cyclists, can be found in Twaddle et al. [82].

3. Performance evaluation of shared spaces

- Besides the new *MOE* for pedestrians based on comfort, in this research, time delay was assumed as the *MOE* for vehicles. The reason is that shared streets represent for motorists nothing but traffic corridors, in which delays are caused by pedestrian crossing. This works states the necessity to evaluate the performance of shared spaces considering together pedestrians' and vehicles' *MOEs*. In fact, certain elements such as street configuration, road regulation or intensity of traffic demand can some times facilitate one type of road user at the expense of the other. Carrying out a joint evaluation of both transport modes provides a full overview of the expected performances of shared spaces.

- Performances in the field of traffic safety were also considered in this work. surrogate safety measures (*SSMs*) for shared spaces, which focus on traffic conflicts, were detected and discussed. The contribution of this work consists in the identification of suitable *SSMs* for shared spaces as well as in the establishment of a method to compute them systematically, once trajectory data are given - from the real-world or the simulation. Moreover, recommendations were given to collect the results in shared space simulation and to draw meaningful conclusions. However, performance measures of traffic safety were not calculated in shared space simulation due to the lacks of the current model, which would have lead to implausible results. Nevertheless, when more reliable shared space models will be available in the future, the detected SSMs can be used to compare traffic safety between alternative scenarios.

- The simulation of shared space scenarios in Chap. 7 has considered the variation of traffic demand - both for vehicles and pedestrians - as well as the longitudinal extension of the shared zone. In order to quantify the effect of these variables on traffic performance, their values were changed one at a time with respect to the baseline scenario. Consequently, the obtained results cannot be generalized to every traffic condition but are related to the situation in the baseline. Future research should deal with the simulation of scenarios, which differ from the baseline in more than one aspect (e.g., changing traffic demand *and* longitudinal extension of the shared zone).

In this way, simulation can show the combined effect of variables. Moreover, it can be stated under which condition (i.e., combination of variables) some given performance thresholds are respected and not exceeded.

Appendices

Appendix A: Publications

Appendix B: Pedestrian O-D matrix

Appendix C: Questionnaire

Appendix D: Calibration of Pedestrian MOE

A Publications

Pascucci, F., Rinke, N., Schiermeyer, C., Friedrich, B. and Berkhahn, V.. Modeling of Shared Space with multi-modal traffic using a multi-layer social force approach. In *Transportation Research Procedia* 10, 316 - 326, 2015. Presented at the 18th Meeting of the EURO Working Group on Transportation (EWGT), 14-16 July 2015, Delft (NL).

Rinke, N., Schiermeyer, C., Pascucci, F., Berkhahn, V. and Friedrich, B.. A multi-layer social force approach to model interactions in shared spaces using collision prediction. In *Transportation Research Procedia* 25, 1249 - 1267, 2017. Presented at the 14th World Conference on Transport Research (WCTRS), 10-15 July 2016, Shanghai (CN).

Schiermeyer, C., Pascucci, F., Rinke, N., Berkhahn, V. and Friedrich, B.. A genetic algorithm approach for the calibration of a social force based model for shared spaces. *In Proceedings of Pedestrian and Evacuation Dynamics 2016*, 485–491. Presented at the 8th International Conference on Pedestrian and Evacuation Dynamic (PED), 17-21 October 2016, Hefei (CN).

Pascucci, F., Friedrich, B.. Evaluation of traffic quality of streets with shared space design. Presented at Heureka ´17 – Optimierung in Verkehr und Transport, 22-23 March 2017. Stuttgart (D).

Schiermeyer, C., Pascucci, F., Rinke, N., Berkhahn, V. and Friedrich, B.. Modeling and solving of multiple conflict situations in shared spaces. In *Proceedings of 12th Conference on Traffic and Granular Flow (PED)*, 19-22 July 2017, Washington D.C. (USA).

Pascucci, F., Vogt, S. and Friedrich, B.. Measuring the quality of traffic flow on urban streets with high pedestrian crossing demand. Presented at the 20th Meeting of the EURO Working Group on Transportation (EWGT), 4-6 September 2017, Budapest (H)

Pascucci, F., Rinke, N., Schiermeyer, C., Friedrich, B. and Berkhahn, V.. Should I stay or should I go? A discrete choice model for pedestrian-vehicles conflicts in shared space. Presented at the 97th Annual Meeting of the Transportation Research Board (TRB), 7-11 January 2018, Washington D.C. (USA).

B Pedestrian O-D matrix

To implement in the simulation the same traffic demand of data survey, 10 m wide areas were created to the sides of the circulation zone and were used as origin/destination for pedestrians (see Fig. B.1). Once each pedestrian in the 30 min interval was assigned to the respective zones, traffic demand was scaled to get hourly values (see Tab. B.1)

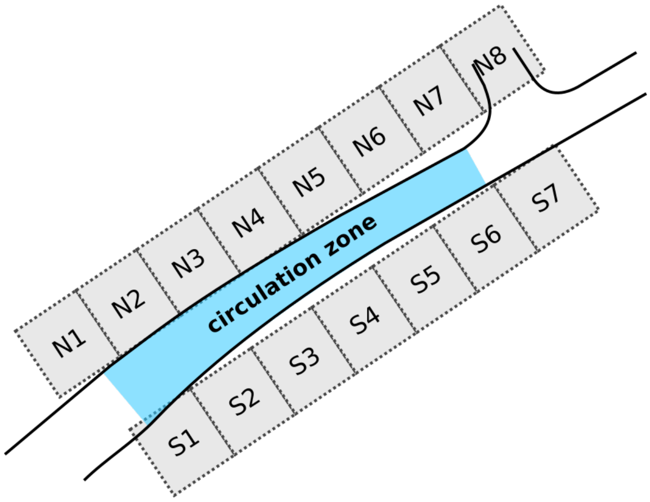


Fig. B.1. Position of the O/D zones

	D	N1	N2	N3	N4	N5	N6	N7	N8	S1	S2	S3	S4	S5	S6	S7
O	**sum**	26	66	60	66	354	374	138	52	16	96	86	314	264	222	102
N1	40									4	30	4	2	0	0	0
N2	32									2	22	8	0	0	0	0
N3	24									2	10	12	0	0	0	0
N4	30									2	10	12	2	2	2	0
N5	562									6	22	44	292	192	6	0
N6	260									0	2	6	16	56	134	46
N7	100									0	0	0	0	10	66	24
N8	52									0	0	0	2	4	14	32
S1	26	0	4	14	8	0	0	0	0							
S2	110	20	26	22	28	12	2	0	0							
S3	110	6	34	10	18	38	4	0	0							
S4	146	0	2	8	6	118	12	0	0							
S5	312	0	0	4	6	178	114	10	0							
S6	266	0	0	2	0	6	168	72	18							
S7	166	0	0	0	0	2	74	56	34							

Tab. B.1. O/D matrix for pedestrians used in the simulation [ped/h]

C Questionnaire

Before starting the questionnaire, respondents were asked to watch a brief presentation which included an explanation of the subject of the survey and technical information to perform the evaluation. The presentation consisted of 16 slides and is reported over the next four pages.

Technische Universität Braunschweig
Institut für Verkehr und Stadtbauwesen
Prof. Dr.-Ing. Bernhard Friedrich

MODIS multi modal intersection simulation

DFG Deutsche Forschungsgemeinschaft

Umfrage zur Bewertung der Qualität des Fußgängerverkehrs in „Shared Space“-Bereichen

Ansprechpartner: M.Sc. Federico Pascucci
f.pascucci@tu-braunschweig.de Tel. 0531-391-66807

Wenn wir als Fußgänger die andere Seite der Straße erreichen wollen, kann es vorkommen, dass wir:

- Entweder sicher **durch das Grün einer Ampel** geführt werden, was allerdings zeitaufwändig ist
- Oder **spontan loslaufen**, wenn wir eine ausreichend große Zeitlücke zwischen zwei Autos finden.

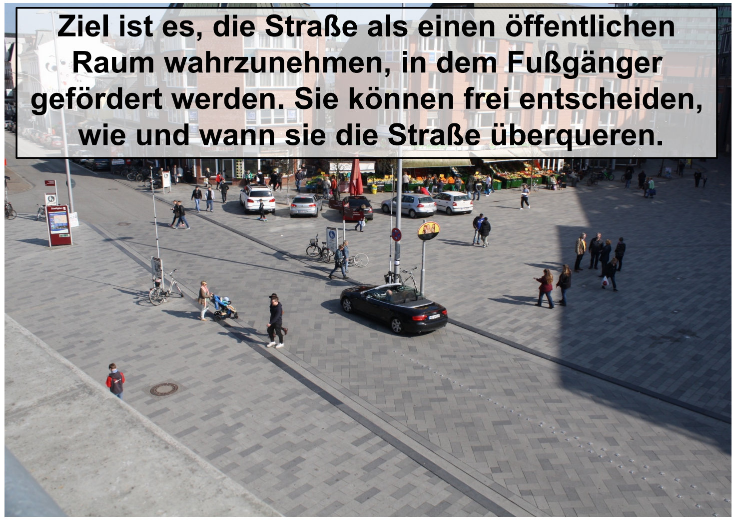
Vielen Dank für Ihre Teilnahme.

Die Umfrage wird zwischen 5 und 10 Minuten dauern.

Wir bitten Sie, 12 Videos zu schauen und anschließend eine Bewertung abzugeben.

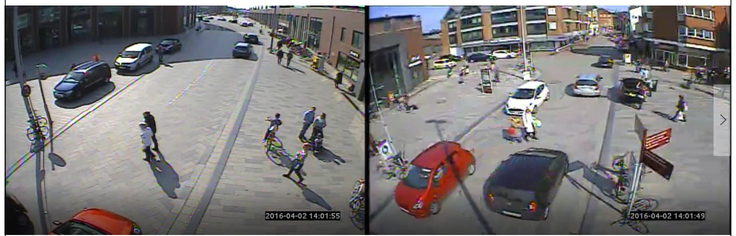
Bitte schauen Sie sich jetzt diese Präsentation an. Mit einem Mausklick erscheint die nächste Folie.

Bei Fragen wenden Sie sich bitten an den Versuchsleiter.

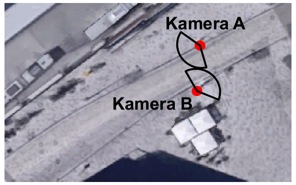


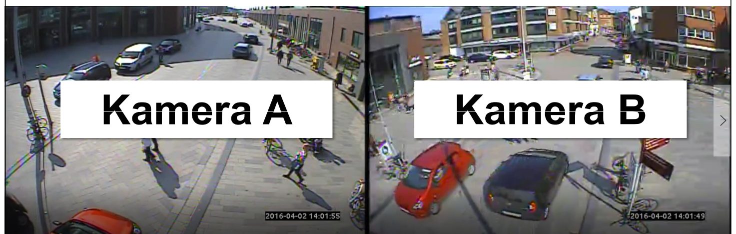
Jedoch ist jede Überquerung eines
„Shared Space“-Bereichs unterschiedlich.

Sie sehen unten zwei
zeitsynchrone Videofenster.

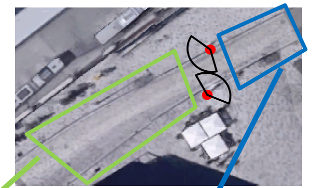


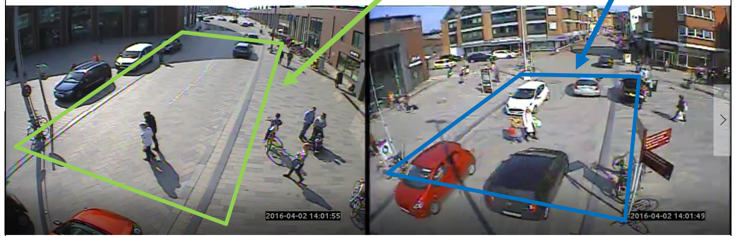
Die Kameras sind
entgegengesetzt aufgestellt.



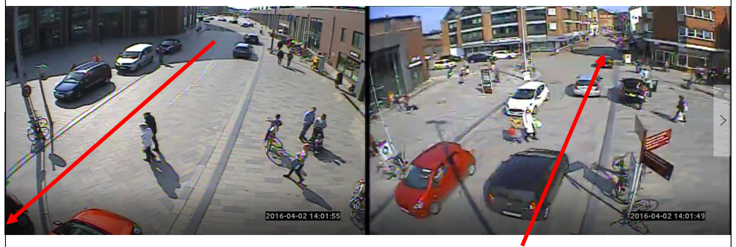


Sie nehmen die Straße in zwei
Bereichen auf.

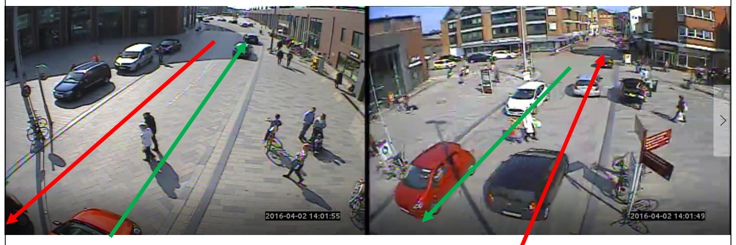




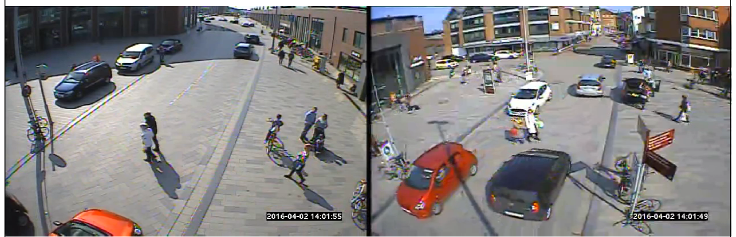
Die Autos, die aus dem linken
Fenster herausfahren, kommen
im rechten Fenster ins Bild.



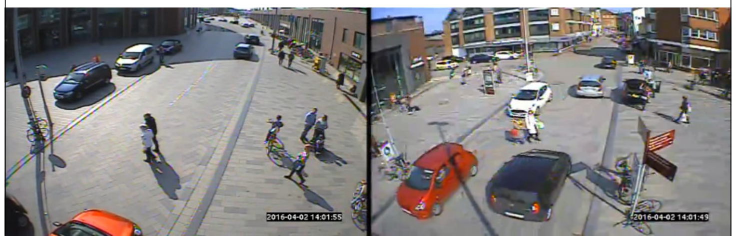
Und andersherum, wie der grüne Pfeil zeigt.



Alles verstanden? Folgen Sie nun mit Ihrem Blick dem weißen Auto!



Alles verstanden? Folgen Sie nun mit Ihrem Blick dem weißen Auto!



Wir bitten Sie nun, den Überquerungsvorgang der Fußgänger in 12 kurzen Videos mit Hilfe einer Skala zu bewerten:

++ sehr angenehm
\+ angenehm
0 neutral
\- unangenehm
-- sehr unangenehm

D

Calibration of Pedestrian MOE

D.1 Main formulation

Predictor $p2$	$Adj.R^2$	k_{p2}	Std. Error	t-statistic	p-value
D	-	-	-	-	-
TE1	0.528	-0.21	0.03	-7.01	**0.0000**
TE2	0.445	0.01	0.03	0.39	0.6755
IV1	0.531	-0.25	0.05	-4.68	**0.0002**
IV2	0.602	0.19	0.03	6.83	**0.0000**
IV3	0.511	0.11	0.03	4.00	**0.0000**
PM1	0.547	-0.18	0.02	-5.71	**0.0000**
PM2	0.500	-0.12	0.03	-3.62	**0.0000**

Tab. D.1. Regression analysis for multilinear models $k_0 + k_{p1} \cdot D + k_{p2} \cdot p2$.
In light of these results, predictor IV2 was included in the model.

Predictor $p3$	$Adj.R^2$	k_{p3}	Std. Error	t-statistic	p-value
D	-	-	-	-	-
TE1	0.659	-0.18	0.03	-5.69	**0.0000**
TE2	0.569	0.03	0.02	1.18	0.2392
IV1	0.565	-0.03	0.06	-0.49	0.6266
IV2	-	-	-	-	-
IV3	0.592	0.07	0.02	2.81	**0.0059**
PM1	0.589	-0.15	0.02	-2.64	**0.0093**
PM2	0.569	-0.04	0.03	-1.13	0.2627

Tab. D.2. Regression analysis for multilinear models $k_0 + k_{p1} \cdot D + k_{p2} \cdot IV2 + k_{p3} \cdot p3$.
In light of these results, predictor TE1 was included in the model.

Predictor $p4$	$Adj.R^2$	k_{p4}	Std. Error	t-statistic	p-value
D	-	-	-	-	-
TE1	-	-	-	-	-
TE2	0.660	0.02	0.02	1.10	0.272
IV1	0.657	-0.03	0.05	-0.48	0.6346
IV2	-	-	-	-	-
IV3	0.675	0.07	0.02	2.61	**0.0102**
PM1	0.668	-0.08	0.02	-2.01	**0.0465**
PM2	0.657	-0.02	0.03	-0.64	0.5211

Tab. D.3. Regression analysis for multilinear models $k_0 + k_{p1} \cdot D + k_{p2} \cdot IV2 + k_{p3} \cdot TE1 + k_{p4} \cdot p4$.
In light of these results, predictor IV3 was included in the model.

Predictor $p1$	$Adj.R^2$	k_{p1}	Std. Error	t-statistic	p-value
D	-	-	-	-	-
TE1	-	-	-	-	-
TE2	0.678	0.03	0.02	1.40	0.165
IV1	0.674	-0.04	0.05	-0.72	0.4743
IV2	-	-	-	-	-
IV3	-	-	-	-	-
PM1	0.682	-0.03	0.02	-1.81	0.0727
PM2	0.673	-0.01	0.03	-0.34	0.7318

Tab. D.4. Regression analysis for multilinear models $k_0 + k_{p1} \cdot D + k_{p2} \cdot IV2 + k_{p3} \cdot TE1 + k_{p4} \cdot IV3 + k_{p5} \cdot p5$.
In light of these results, no predictor was included in the model.

D.2 Alternative formulation

Differently to the main formulation, conflict-related variables (IV1,IV2 and IV3) were not considered. According to Tab. D.1, PM1 was included in the model instead of IV2. The following table show the next steps of the analysis.

Predictor $p1$	$Adj.R^2$	k_{p1}	Std. Error	t-statistic	p-value
D	-	-	-	-	-
TE1	0.667	-0.11	0.03	-6.31	**0.0000**
TE2	0.553	0.01	0.02	0.36	0.7193
PM1	-	-	-	-	-
PM2	0.553	0.01	0.04	0.30	0.7619

Tab. D.5. Regression analysis for multilinear models $k_0 + k_{p1} \cdot D + k_{p2} \cdot PM1 + k_{p3} \cdot p3$. In light of these results, predictor TE1 was included in the model.

Predictor $p1$	$Adj.R^2$	k_{p1}	Std. Error	t-statistic	p-value
D	-	-	-	-	-
TE1	-	-	-	-	-
TE2	0.666	0.01	0.02	0.75	0.4566
PM1	-	-	-	-	-
PM2	0.665	0.02	0.04	0.66	0.5134

Tab. D.6. Regression analysis for multilinear models $k_0 + k_{p1} \cdot D + k_{p2} \cdot PM1 + k_{p3} \cdot TE1 + k_{p3} \cdot p3$. In light of these results, no predictor was included in the model.

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